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Spectrally Selective Glazings for Residential Retrofits

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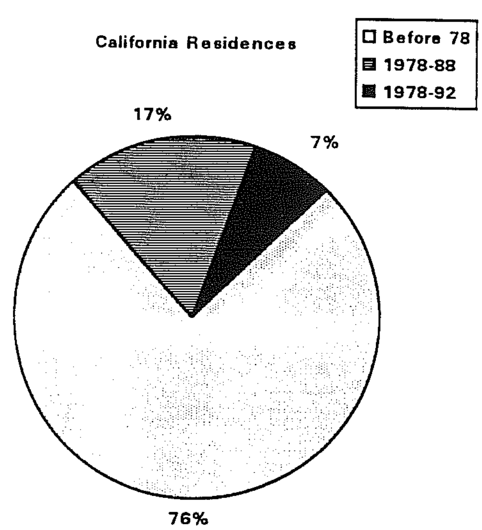
Introduction

A large fraction of California's energy consumption and peak demand results from the need to cool residential buildings with high levels of solar heat gain transmitted through windows. For example, single family residences with central air conditioning built before 1978 consume from approximately 800 kWh per household in the Sacramento Municipal Utility District (SMUD) territory to 2,000 kWh per household within the northern Pacific Gas and Electric (PG&E) and Southern California Edison (SCE) central valley and inland territories. For a new demonstration home being built in the Sacramento area, SMUD reported that 52% of the peak summer cooling load was due to solar heat gain from windows. In cooling-dominated portions of California, where this energy problem is most severe, clear single-pane glass having the highest solar heat gain of any glazing type, is the most prevalent glazing found in existing residences.

Of the current residential building stock, 76% were built prior to the 1978 energy efficiency standards (CEC, 1990). Virtually all of these buildings will have clear single glass. Solar control glazing such as tinted glass and non-selective coatings can reduce solar heat gain at the expense of illumination and clarity of view which is required for architectural and personal preference reasons. Newer spectrally selective glazings can reduce solar heat gain with minimal loss of illumination and view. Only about 7% of California homes were built after advanced spectrally selective glazings became widely available. We do not yet have any estimates of how many of these homes actually have spectrally selective



glazings. These emerging window technologies are only now being incorporated into state standards and utility incentive programs for new construction. Thus, the existing residential sector can offer a substantial opportunity for energy savings in California

In this report, we first evaluate the existing retrofit products. Then we calculate the effect of the retrofit on cooling requirements and peak demand. We discuss our efforts to develop retrofit prototype glazing systems using existing products. Finally we describe the directions for materials research needed to put retrofit coatings on the same level as products for new construction.

Survey of Existing Products

Spectrally selective glazings are a relatively new class of window products that admit a high proportion of visible daylight while excluding most of the heat gain arising from the solar infrared. Figure 2 represents the ideal spectrally selective glazing which would have a transmission window spanning most of the visible portion of the solar spectrum and high reflection in the ultraviolet and infrared. Some clipping of the red and violet extremes of the visible region is acceptable because the eye makes inefficient use of these colors. Although some color sensitivity is lost in clipping of the visible, a significant additional reduction in solar transmission can be achieved. Too much clipping, however, can compromise the neutral appearance of the light and view. If maximum daylight or night

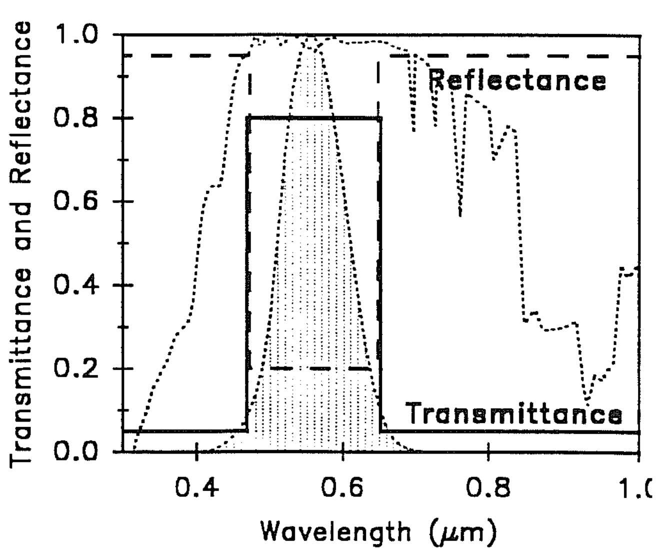


Figure 2. Solar spectral properties of an ideal spectrally selective glazing. The shaded region of the solar spectrum represents the response of the eye to light.

view is not required, the height of the transmission band can be lowered to further reduce solar heat gain.

Examples of products in use today are shown in Figure 3. Some formulations of green or blue glass provide the same high durability as clear glass at approximately the same price. These glasses, however, cut out some of the red end of the visible spectrum and they also absorb rather than reflect the infrared. Some of this absorbed radiation will reradiate to the interior, especially in single glazing. The closest approach to the ideal of Fig. 2 is attained using silver-based multilayer thin films, although the transmission cutoffs of available products could be sharpened using more layers (at considerable cost). Silver-based films are very reliable in sealed insulated glass units, but in retrofit configurations their optical properties are susceptible to degradation.

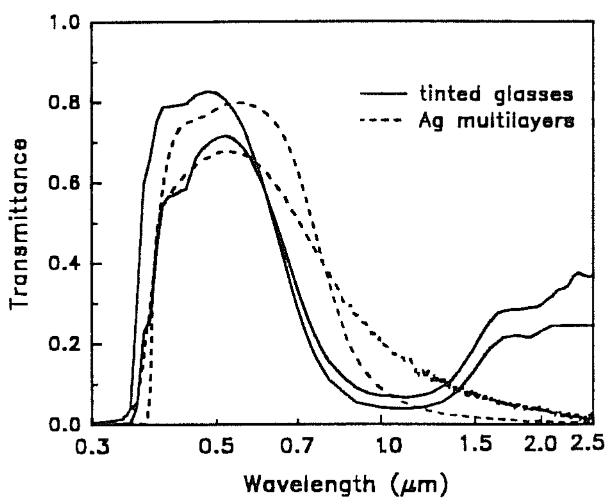


Figure 3. Solar transmission spectra of the best available spectrally selective glazings.

Data on optical and thermal properties of available spectrally selective products was taken from the product literature, measured in our laboratory, or calculated using WINDOW 4.0 (Arasteh, 1989) from raw data supplied by manufacturers. The two most important performance variables for spectrally selective glazings are the shading coefficient (SC) and the visible transmittance T_V. The SC is a measure of total solar heat gain including both the directly transmitted solar radiation as well as the indirect component of inward flowing heat due to absorption by the glazing. Thus, SC makes a fairer comparison between absorbing and reflecting glazing than the solar transmittance alone. Figure 4 shows the distribution of retrofit products in typical configurations as measured by these parameters. Ideally, the coatings should have a low SC and a high T_V, meaning that they should be as close to the lower right corner of the graph as possible. Because daylight also carries heat into the room, it is not possible to have zero shading coefficient with finite visible transmission. Thus, there is a "forbidden zone" in which no glazing can exist. We also define a somewhat subjective "color zone" in which there is no possibility of creating a glazing which is colorless. In the "neutral zone" glazings may but do not necessarily have a neutral color.

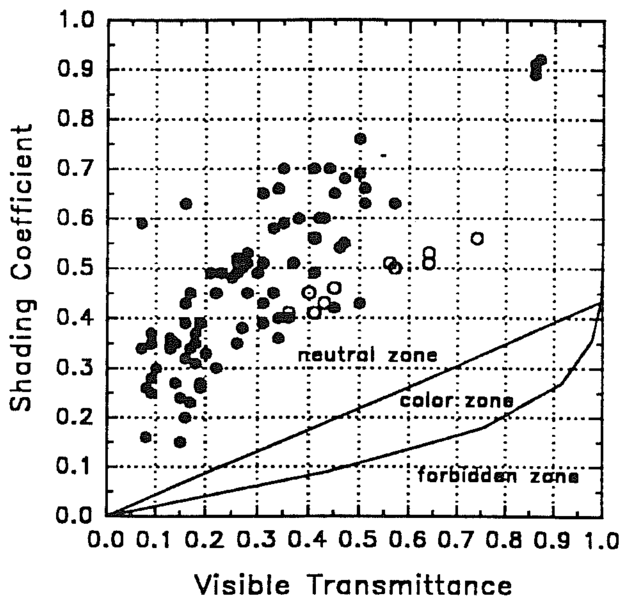


Figure 4. Spectral selectivity of coatings on plastic film that are laminated to clear or heat-absorbing glasses. Open symbols represent new products that have not been fully tested.

By comparison to Fig. 5, which shows products mainly intended for new construction, the retrofit products are shifted away from the ideal. Until recently, in the transmission range above 0.5, no laminate products were available with high selectivity. Two factors are involved in this technology gap. First, coating on plastic film is more difficult than coating on glass because of problems with adhesion, temperature range of the substrate, diffusion, and bending stress. Second, the edges of the coating in a retrofit installation are prone to damage from water vapor and corrosive agents in the atmosphere. The materials used in highly selective coatings are especially prone to this type of damage. Furthermore, most laminate manufacturers have been content to produce less spectrally selective coatings such as aluminized polyester, because of lower cost, ease of handling, and the existence of a ready market. These manufacturers now perceive, however, that plastic laminates must catch up to their glass counterparts. Monsanto and Southwall have developed a new type of laminate coating called Solarflex which has spectral selectivity nearly equal to the best coatings on glass, but with less durability outside a sealed environment.

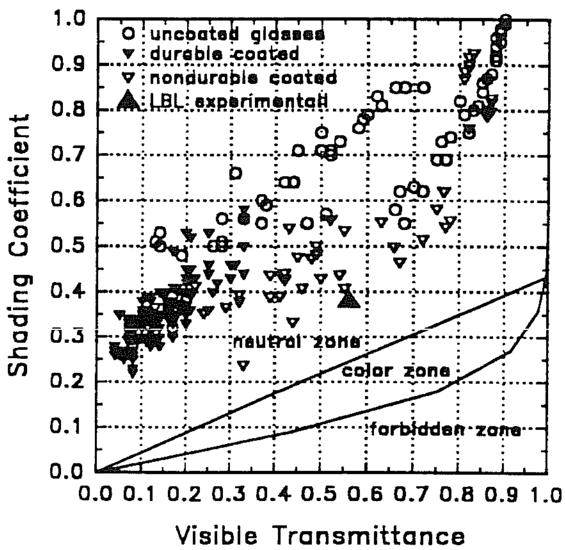


Figure 5. Spectral selectivity of commercial glasses and coatings applied to glass.

Parametric Cost-Effectiveness Study

Introduction

This section will focus on the potential energy savings that may result with the introduction of spectrally selective glazings to the residential retrofit market. By clarifying the relationship of the glazing characteristics to energy consumption and cost, we intend to identify the key building and climatic parameters that have a significant impact on the feasibility of this proposed energy conservation measure. This analysis consists of defining the relationship of cooling energy cost, cooling peak demand, and chiller size to the glazing shading coefficient for various building configurations in five cooling-dominated climates in California. From the product manufacturers and the construction industry standpoint, this analysis will provide the range of annual cost savings that can be expected given variable production and installation costs. From the perspective of the material scientist, it may serve to define optimum glazing characteristics for further product development. These energy performance data can also be used by utilities for demand side management programs and to assist homeowners in evaluating the cost-effectiveness of glazing product options.

This reduction in the shading coefficient over conventional glazings will result in four changes related to energy performance. 1) We can expect cooling energy to decrease since solar gains will be reduced due to a lower shading coefficient. 2) Required heating energy will increase due to a reduction in solar gains. This may be offset, however, by a reduction in thermal conductance due to possible reduced emissivity in some configurations. Since the cost ratio of the heating fuel, typically natural gas, to electricity is low, the significance of increased heating diminishes with respect to total cost. 3) The summer peak demand due to cooling will also decrease due to a reduction in solar gains, and 4) since peak demand is used to size the cooling equipment, a downsizing of the air conditioning unit can also be expected if the homeowner wishes to replace or upgrade the existing system.

Description of the Simulation Model

We have used a computer simulation program to determine the magnitude and trends of the resultant energy performance due to the shading coefficient. The DOE-2.1D Building Energy Simulation Program (Birdsall et al, 1990) allows one to numerically simulate the thermodynamic behavior of a building, to test the sensitivity of this behavior to selected building parameters and to optimize this parameter through an iterative process. A 1,540 square foot single story ranch prototype, derived from comprehensive building simulation development work (Sullivan et al, 1991), was used for the basis of this analysis. Additional parametrics were performed to capture the variety of building characteristics prevalent in California residential buildings; e.g. overhangs, interior drapes, concrete slab on grade construction, etc. A description of the geometry, construction, and equipment used for the prototype is provided in Table 1. A more detailed description of the development of these housing characteristics can be found in a study by the LBL Energy Analysis Program (1985).

The Title-24 California Residential Energy Code adopted fenestration standards after 1978; hence, we are modeling the typical pre-1978 housing stock that has clear single-pane glazing. Two surveys, completed for the Western Region of the United States (EIA, 1984 & 1987) and for California (CEC, 1990a) allowed us to draw general conclusions regarding the average construction and size of the existing housing stock. Energy consumption data was also provided by these surveys. According to the California survey, our prototype may overestimate the cooling energy consumption due to possible inaccurate modeling of occupant behavior, thermostat settings, and siting of the building in

Table 1. Building Description of the DOE-2.1D Simulation Prototype

Building Floor Area	
Ranch	1,540 sq.ft.
Two-story*	3,080 sq.ft.
Building Geometry	
Width	39.2 ft.
Depth	39.2 ft.
Floor-to-ceiling height	8 ft.
Crawl space	2.75 ft.
Concrete slab on grade*	4 in.
Construction	
Wood frame with stucco exterior and drywall interior.	
Low insulation level: R6 walls, R11 roof, R0 floor.	
Medium insulation level: R11 walls, R30 roof, R5 floor.*	
Glazing	
Shading coefficient	0 to 1.0 at increments of 0.25.
Visible transmittance	1.0
U-value (single-pane)	1.3 Btu/hr-sq.ft-°F
U-value (double pane)*	0.5 Btu/hr-sq.ft-°F
Area: 0 to 12% WFR, 40 combinations for the four cardinal orientations.	
Area: 14% WFR, distributed equally on all four orientations.*	
Internal Loads	53,963 Btu/day
Occupant Loads	10,163 Btu/hr
Infiltration (Average, Sherman-Grimsrud)	0.0005 % of total floor area
Mechanical	
Gas furnace and central air conditioning.	
Heat pump.*	
Electricity Rate	$0.13 per kWh
Gas Rate	$6.00 per MBtu
Built-up Area*	
39.42ft wide x 8ft high adjacent residences spaced 20ft away from each facade.	
Interior Shade Management*	
Reduce solar heat gain by 40% when direct solar gain exceeds 30 Btu/sq.ft.	
Overhang*	
2 foot projection at head of window matching the exact width of the window.	

* These parameters were varied individually over the base case prototype configuration for the 14% glazing area.

built-up metropolitan areas. Since cooling energy was not conclusively correlated in the California survey due to the small sample size, we have provided additional building parameters that will account for the concerns voiced in this survey. A comprehensive project using end use metering data and an extensive utility mail survey provided by the California Energy Commission is currently underway by the Energy Analysis Program at Lawrence Berkeley Laboratory to develop residential prototypes per vintage and is due to be released at the end of 1992.

Five climates were selected based on population and the severity of the climate. Blythe was chosen to represent the extreme of the cooling-dominated climates in California; the cooling degree days (CDD, base 75_F) for this location are 2,280. Red Bluff, Fresno, Riverside, and Sacramento all have CDD less than 700, but have a substantial population. Other areas, such as the Los Angeles metropolitan areas (coastal climate), all fall under 200 CDD and thus are not considered in this analysis. Weather data have been provided for these five cities in Table 2.

In 1982, the California Public Utilities Commission redesigned the tariff structure to include a "baseline" allowance based on demographic studies and a climatic zoning of the utility territories (Doughty, 1992). Housing in these territories are allowed a winter and summer allocation of energy use per day, above which there is an additional charge. The electricity and gas rates for the associated utility areas have been provided in Table 3. Initial simulations were run on our base case prototype to determine if and when our prototype exceeded this baseline allowance per climate. For all climates, the baseline was exceeded throughout the winter and summer billing months for a 12% window-area-to-floor-area ratio (WFR) equally distributed between each facade with a shading coefficient of 0.5. Therefore, we have decided to simplify the time-of-use rate structure by using a fixed electricity and gas rate that is slightly higher than the baseline rate throughout the entire year (Table 1).

Method

We identified three parameters that we wished to relate to the glazing shading coefficient: the climate, the orientation of the window, and the area of the glazing. In order to isolate the effect of each parameter, a large database was created by simulating the full range of values for each of these parameters for the base case prototype, then using multiple regression analysis to correlate these parameters to the building energy performance. This analysis method is well established and is fully documented in a study by Sullivan (1991).

Table 2: Weather Data for Five California Climates

Location	Latitude	Longitude	Altitude (ft)	CDD (75°F)	HDD (65°F)	No. Days Max. Temp. > 90°F	Average Annual Dry-Bulb Temp. (°F)	Average Annual Wet-Bulb Temp. (°F)
Blythe	33.6	114.6	390	2,280	1,065	168	74	55
Red Bluff	40.2	122.2	342	679	2,904	97	62	51
Fresno	36.7	119.8	326	417	2,685	94	62	52
Riverside	33.9	117.2	1543	252	2,103	80	62	52
Sacramento	38.5	121.5	17	191	2,764	69	60	52

Location	Average Daily Total Vertical Solar for surface facing (Btu/hr-sq.ft.):			
	North	East	South	West
Blythe	403	1,009	1,228	1,000
Red Bluff	411	936	1,226	963
Fresno	410	986	1,180	965
Riverside	444	942	1,290	1,027
Sacramento	423	972	1,232	994

Table 3. Energy Rates for California Utility Districts Residential Customers in a Single-Family Dwelling with Gas Space Heating

Electricity Cost	Baseline Cost $/kWh	Over Baseline $/kWh	Baseline Allowance kWh/day	Billing Months
Southern California Edison (Effective 1/20/92)				
Blythe	$0.10629	$0.14131	39.3	Jun - Sep
	$0.10629	$0.14131	10.9	Oct - May
Riverside	$0.10629	$0.14131	10.9	May - Oct
	$0.10629	$0.14131	9.2	Nov - Apr
Pacific Gas & Electric (Effective 1/1/92)				
Red Bluff & Fresno	$0.11107	$0.13865	15.7	May - Oct
	$0.11107	$0.13865	11.8	Nov - Apr
Sacramento Municipal Utility District (Effective 1/1/1992)				
Sacramento	$0.08058	$0.12695	23.4	May - Oct
	$0.07378	$0.11814	20.7	Nov - Apr

Natural Gas Cost	Baseline Cost $/MBtu	Over Baseline $/MBtu	Baseline Allowance MBtu/day	Billing Months
Southern California Gas (Effective 1/1/92)				
Blythe & Riverside	$4.67550	$6.72580	6.2	May - Oct
	$4.67550	$6.72580	16.6	Nov - Apr
Pacific Gas & Electric (Effective 1/1/92)				
Red Bluff & Fresno	$5.04030	$8.24210	5.0	May - Oct
	$5.04030	$8.24210	24.0	Nov - Apr
Sacramento	$5.04030	$8.24210	6.0	May - Oct
	$5.04030	$8.24210	24.0	Nov - Apr

The shading coefficient was varied at increments of 0.25 from 0 to 1.0. Forty combinations of glazing area varying from 0% to 12% of the floor area or from 0% to 60% of the exterior wall area per facade were modeled. The four cardinal directions were considered for window orientation. Hence, for each city, 200 prototype configurations were correlated using the equation:

$$Ei = \beta 1i \times U \times Ai + \beta 2i \times (U \times Ai)^2 + \beta 3i \times SC \times Ai + \beta 4i \times (SC \times Ai)^2 \quad (1)$$

where,

E = Annual incremental cooling or heating energy consumption (kBtu) due to the glazing or,

E = Annual incremental cooling or heating peak demand (kBtu/hr) due to the glazing.

and

ß	=	Regression coefficients for the energy performance variable.
SC	=	Shading coefficient of the glazing.
U	=	U-value of the glazing, fixed at 1.3 Btu/ft^2-hour-_F.
A	=	Area of the window (ft^2).
i	=	North, east, south, or west orientation of the window.

The *incremental* cooling or heating peak demand or energy consumption due to the glazing area can be determined for any orientation and for any combination of glazing area and shading coefficient using the equation above. Incremental is defined as the difference in energy use or demand between the prototype building with windows and the same prototype without windows. The regression coefficients, ß1 through ß4, are provided for each city in Tables 4a and 4b. Correlation of the energy consumption calculated by the DOE-2.1D simulation program to that predicted by the above equation is very good (e.g., R^2=0.9997 for the cooling energy consumption of the base case prototype in Blythe).

In order to encompass the range of housing characteristics, we have run a second set of parametric simulation runs. The relationship of a variant of the base case prototype to the base case is known to be linear with changes in geographic location (Sullivan et al, 1985). To establish this proportional relationship, we have simulated a subset of the combinations studied for the base case prototype. A fixed glazing area, 14% window-to-floor-area ratio (WFR), was assumed to be equally distributed between each of the four cardinal directions. The shading coefficient was assumed to be 0.5, the lower limit of what may be attained with spectrally selective coatings or films, or 1.0, the prevalent single pane clear

Table 4a. Regression Coefficients for the Basecase Prototype

		Blythe	Red Bluff	Fresno	Riverside	Sacramento
Cooling Energy (kBtu)						
B1N	U x A	13.77870	5.64143	2.67241	3.49893	3.00480
B2N	(U x A)2	-0.01400	-0.01083	-0.00759	-0.01247	-0.00858
B3N	SC x A	31.58294	18.66514	16.16866	11.48078	11.77713
B4N	(SC x A)2	0.01231	0.02175	0.02271	0.06165	0.03674
B1E	U x A	13.30121	4.58219	2.36985	2.74039	2.88546
B2E	(U x A)2	-0.01779	-0.01026	-0.01031	-0.01373	-0.01177
B3E	SC x A	76.82624	53.39813	39.80681	33.77791	35.02051
B4E	(SC x A)2	0.00605	-0.00703	0.02464	0.08045	0.04976
B1S	U x A	13.72540	5.57701	3.39517	3.16750	3.78119
B2S	(U x A)2	-0.01869	-0.01521	-0.01314	-0.01463	-0.01389
B3S	SC x A	69.05284	50.77794	34.51679	32.94584	31.46500
B4S	(SC x A)2	0.06397	0.07064	0.07956	0.15466	0.09233
B1W	U x A	13.79493	5.96910	2.73135	3.11466	3.32642
B2W	(U x A)2	-0.02019	-0.01717	-0.01168	-0.01409	-0.01402
B3W	SC x A	108.17886	63.16051	58.07820	41.12384	46.17711
B4W	(SC x A)2	0.03841	0.05972	0.07225	0.13392	0.09762
Peak Cooling Energy (kBtu/hr)						
B1N	U x A	0.01587	0.01832	0.00801	0.00768	0.00641
B2N	(U x A)2	-0.00001	-0.00001	-0.00001	0.00000	0.00000
B3N	SC x A	0.01800	0.01803	0.01629	0.02114	0.01805
B4N	(SC x A)2	-0.00001	0.00000	-0.00001	-0.00002	-0.00004
B1E	U x A	0.01513	0.01616	0.00747	0.00737	0.00646
B2E	(U x A)2	-0.00001	-0.00001	-0.00001	0.00000	0.00000
B3E	SC x A	0.02027	0.03303	0.01969	0.03309	0.01997
B4E	(SC x A)2	-0.00002	-0.00007	-0.00001	-0.00004	-0.00004
B1S	U x A	0.01536	0.01769	0.00759	0.00793	0.00843
B2S	(U x A)2	-0.00001	-0.00001	0.00000	0.00000	-0.00001
B3S	SC x A	0.01920	0.03966	0.02210	0.02956	0.01096
B4S	(SC x A)2	-0.00001	-0.00001	-0.00003	-0.00002	0.00011
B1W	U x A	0.01599	0.01911	0.00788	0.00735	0.00831
B2W	(U x A)2	-0.00001	-0.00002	-0.00001	0.00000	-0.00001
B3W	SC x A	0.09049	0.07784	0.08212	0.04238	0.06964
B4W	(SC x A)2	0.00000	-0.00001	-0.00003	0.00004	-0.00003

Table 4b. Regression Coefficients for the Basecase Prototype

		Blythe	Red Bluff	Fresno	Riverside	Sacramento
Heating Energy (kBtu)						
B1N	U x A	53.32760	109.68186	97.28622	90.58389	107.25669
B2N	(U x A)2	-0.01029	-0.02406	-0.01743	-0.02087	-0.02465
B3N	SC x A	-33.49582	-49.86541	-52.21918	-66.86439	-55.60658
B4N	(SC x A)2	0.09966	0.10213	0.11695	0.22051	0.11015
B1E	U x A	54.90415	110.94347	99.75901	93.49271	109.26328
B2E	(U x A)2	-0.01981	-0.03162	-0.03212	-0.03089	-0.03580
B3E	SC x A	-84.96649	-110.20618	-139.85767	-140.82162	-139.98448
B4E	(SC x A)2	0.22421	0.24889	0.32847	0.41249	0.32406
B1S	U x A	55.53752	113.18677	101.65434	93.75426	111.86658
B2S	(U x A)2	-0.02003	-0.03544	-0.03272	-0.02788	-0.03945
B3S	SC x A	-131.22641	-185.33363	-193.16631	-205.19305	-210.19601
B4S	(SC x A)2	0.41006	0.46419	0.56228	0.72120	0.56549
B1W	U x A	53.68393	110.82391	98.41680	89.99171	109.25614
B2W	(U x A)2	-0.01039	-0.02867	-0.01794	-0.01704	-0.02744
B3W	SC x A	-52.28018	-76.05755	-75.77312	-107.24685	-76.93915
B4W	(SC x A)2	0.15580	0.19593	0.20242	0.36126	0.17747
Peak Heating Energy (kBtu/hr)						
B1N	U x A	0.04501	0.04552	0.03588	0.03607	0.03111
B2N	(U x A)2	-0.00003	-0.00001	0.00001	0.00001	0.00002
B3N	SC x A	0.00570	0.00948	0.05370	0.05711	0.10234
B4N	(SC x A)2	-0.00002	-0.00004	-0.00035	-0.00039	-0.00064
B1E	U x A	0.04490	0.04495	0.03250	0.03429	0.02841
B2E	(U x A)2	-0.00003	-0.00001	0.00000	0.00000	0.00003
B3E	SC x A	0.00644	0.01304	0.06454	0.07309	0.10495
B4E	(SC x A)2	-0.00002	-0.00005	-0.00039	-0.00045	-0.00068
B1S	U x A	0.04543	0.04589	0.03627	0.03949	0.03247
B2S	(U x A)2	-0.00003	-0.00001	0.00000	-0.00001	0.00001
B3S	SC x A	0.00572	0.01498	0.05945	0.06575	0.11614
B4S	(SC x A)2	-0.00002	-0.00005	-0.00035	-0.00040	-0.00067
B1W	U x A	0.04573	0.04687	0.05078	0.04434	0.06532
B2W	(U x A)2	-0.00003	-0.00002	-0.00005	-0.00003	-0.00009
B3W	SC x A	0.02352	0.03155	0.08690	0.08633	0.17694
B4W	(SC x A)2	-0.00005	-0.00008	-0.00045	-0.00047	-0.00098

glazing type in most existing pre-1978 homes. The *total building* cooling energy use and peak demand were determined for the alternate characteristics and then related directly to the base case energy performance for each of the five cities.

An equation for determining the required shading coefficient given a desired incremental heating and cooling energy cost per square foot of glazing and a given orientation and area of glazing can be derived using the quadratic equation with the regression equation provided above:

$$SC_i\ req = [-\ b\ +\ (\ (b^2\ -(4ac)\ )^{0.5}\ ]\ /\ [2a] \qquad (2)$$

where

$a = (j \times ß4i \times Ai^2) + (k \times \mu 4i \times Ai^2)$

$b = (j \times ß3i \times Ai)\ + (k \times \mu 3i \times Ai)$

$c = j \times [\ (ß1i \times U \times Ai)\ +\ (ß2i \times (U \times Ai)^2)$

$\quad +\ k \times [\ (\mu 1i \times U \times Ai)\ +\ (\mu 2i \times (U \times Ai)^2)$

$\quad -\ \ ECi \times Ai$

$EC_i = EC_i\ (SC_{existing})\ -\ EC_{desired}$

where,

SC_{req} = Required shading coefficient of the retrofit glazing for a desired energy cost savings.

EC_{des} = Desired incremental annual energy cost savings ($\$/ft^2$-glazing).

EC = Annual incremental heating and cooling energy cost savings ($\$/ft^2$-glazing).

SC_{exist} = Shading coefficient of the existing glazing.

j = Electricity cost ($/kWh) / 3.414426 (kBtu/kWh).

k = Gas cost ($/MBtu) / 1000.

ß = Regression coefficients for the incremental cooling energy due to the glazing.

μ = Regression coefficients for the incremental heating energy due to the glazing.

U = U-value of the glazing, fixed at 1.3 Btu/ft^2-hour-_F.

A = Area of the window (ft^2).

i = North, east, south, or west orientation of the window.

An illustration of how this relationship can be used to define the boundary conditions of the required shading coefficient per climate will be given in the following section.

Discussion

We will discuss the key building and climatic parameters that have the most significant impact on the feasibility of spectrally selective glazings. All energy and cost results are presented on a per square foot of glazing area basis to facilitate direct comparisons to installation and material costs.

The orientation of the glazing has the most significant impact on the cost-effectiveness of using spectrally selective glazings for a given climate (Figure 6a-6e). The largest contributor to cost is the cooling energy component, 10% (north) to 30% (south) of which is due to the glazing solar gain component. Variable hourly vertical insolation values with respect to orientation (Table 2) and the thermal lag provided by the building mass contributes to the differences in cooling energy with orientation. For all climates, the incremental cooling energy cost due to a west facing window is approximately 40% more than that required for a south or east facing window. The incremental cooling energy cost for a north facing window is approximately 50% less than that of a south or east facing window. South and east facing windows account for approximately the same incremental cooling energy cost. With respect to climate, all cities except for Blythe yield an incremental cooling energy savings of \$0.40 to \$1.50/ft^2-glazing-year if a single pane of clear glass with a shading coefficient of 1.0 is replaced with a single pane unit of spectrally selective glazing with a shading coefficient value of 0.5. For the extreme climate of Blythe, these savings range from \$2.15 for a west facing window to \$0.50 for a north facing window.

The incremental cooling energy cost per square foot of glazing is relatively insensitive to the area of glass used. Figure 7 illustrates this concept for the four glazing orientations in Blythe. For window areas ranging from 2% window-to-floor area ratio (WFR) to 12% WFR (SC=0.50), the incremental cooling energy cost decreases from \$1.98 to \$1.88/ft^2-glazing (5%) for south facing glazing and \$2.09 to \$1.92 (8%) for east facing glazing. However, the incremental cooling energy savings is sensitive to variations in glazing area depending on orientation: from \$1.37 (2%WFR) to \$1.66/ft^2-glazing (12% WFR) or a 21% difference for south facing glazing and \$1.47 to \$1.50/ft^2-glazing (2% difference) for east facing glazing (SC reduction from 1.0 to 0.5).

The incremental cooling peak demand due to the glazing is determined by the maximum energy use that occurs for one hour of the summer. This quantity is largely dependent on the glazing solar gains that occur for that peak hour and, to a lesser extent, the glazing

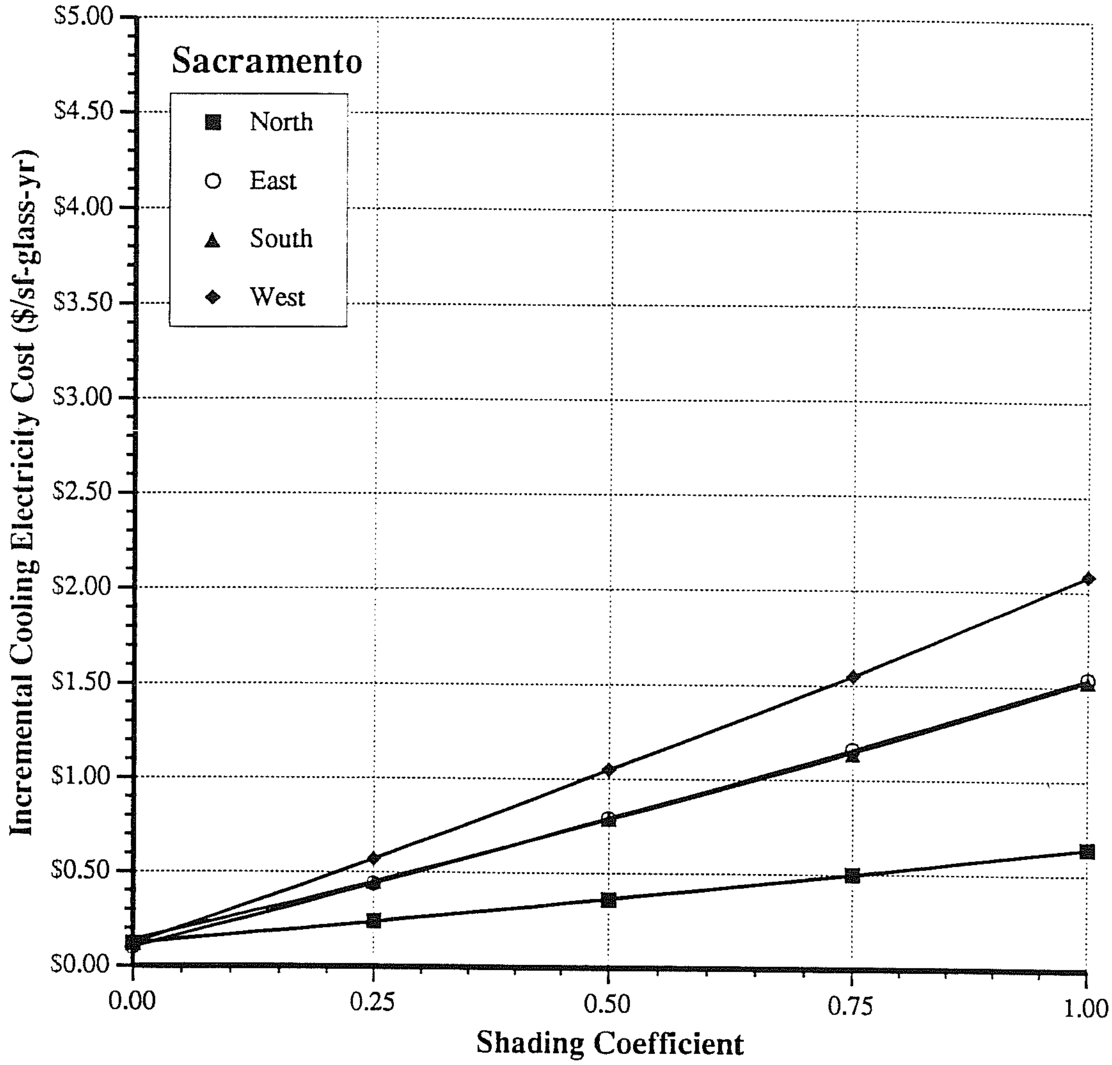


Figure 6a. Incremental annual cooling electricity cost per square foot of glazing for a 1,540 square foot residential home in Sacramento California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

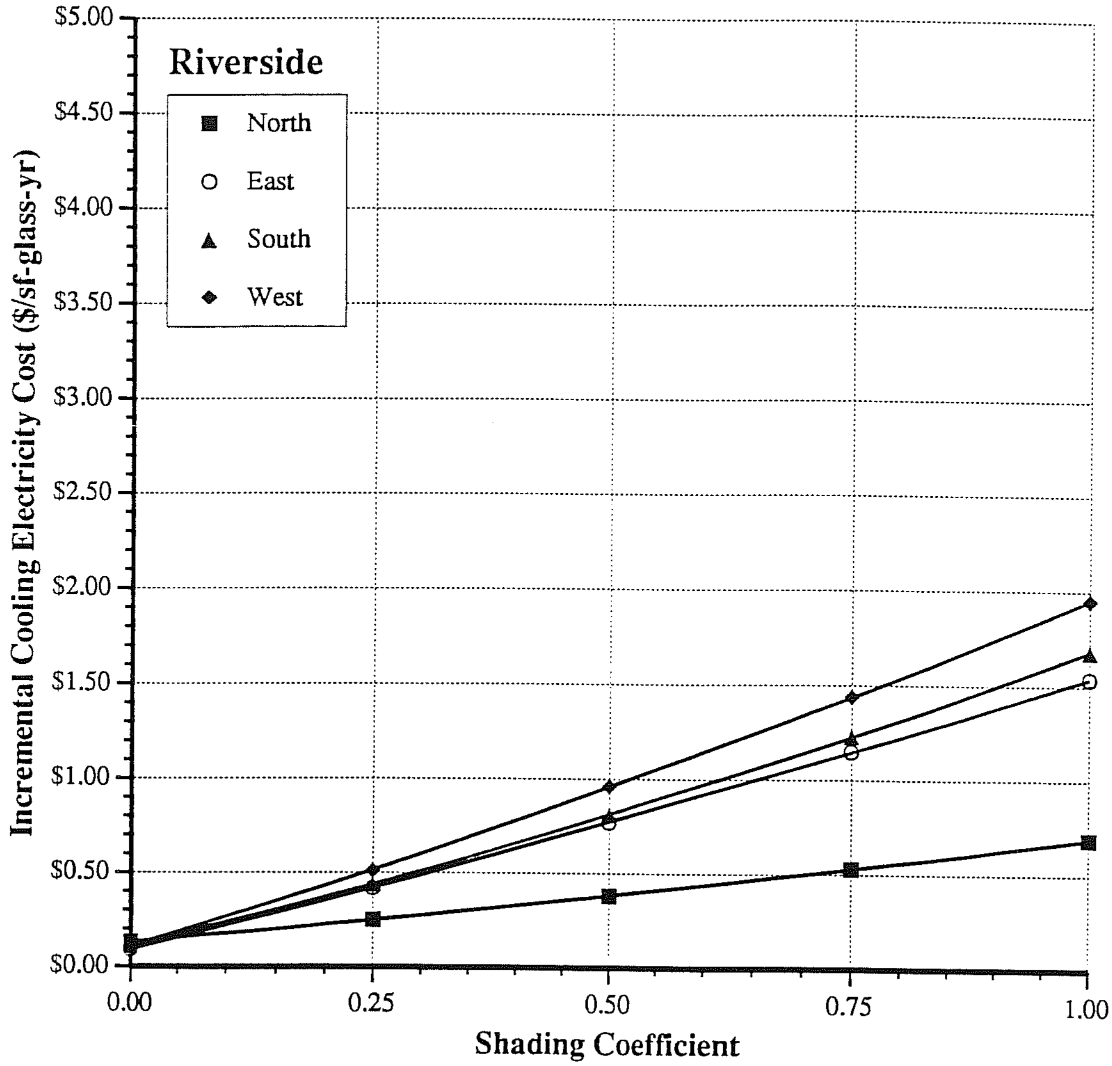


Figure 6b. Incremental annual cooling electricity cost per square foot of glazing for a 1,540 square foot residential home in Riverside, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

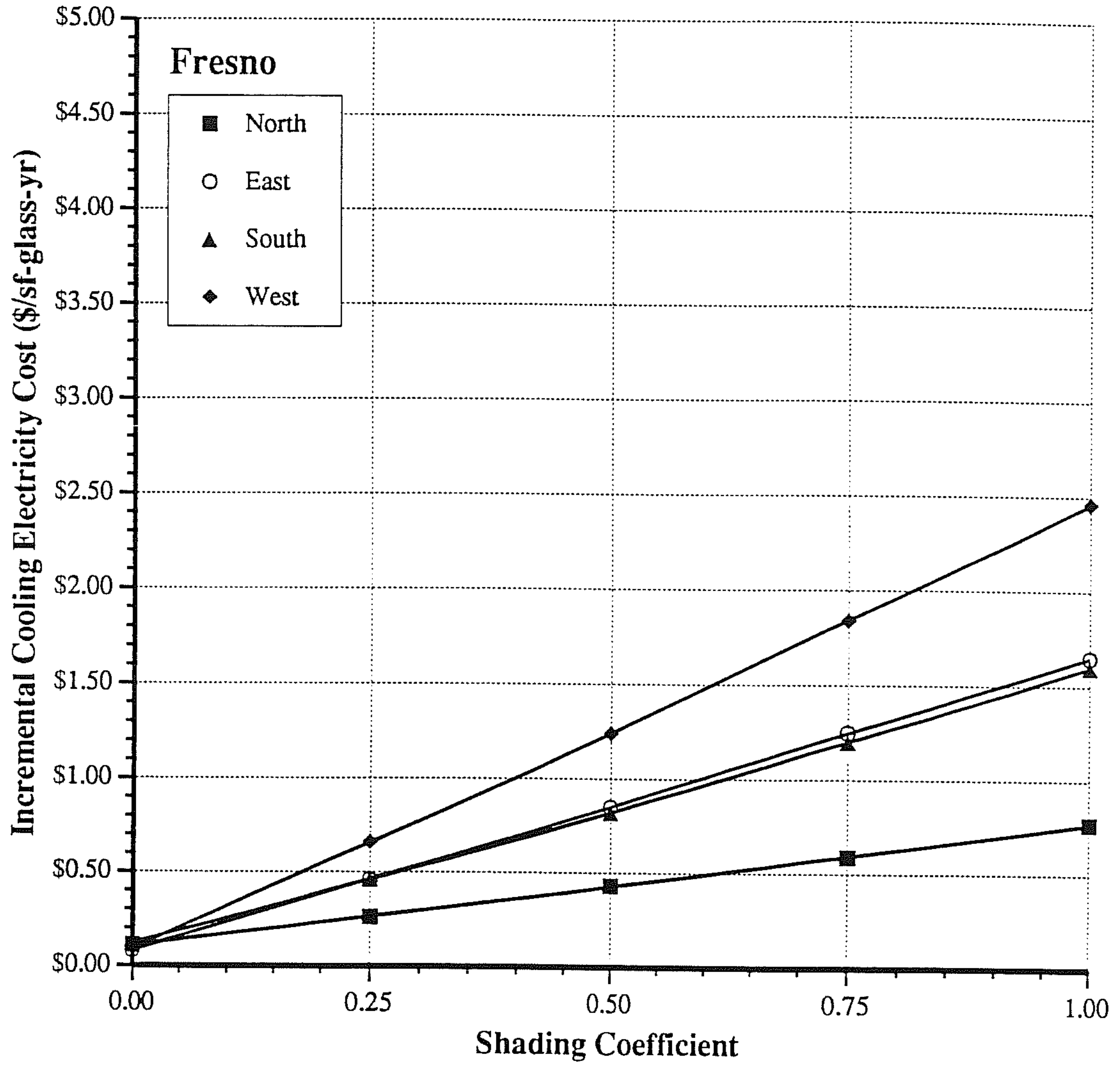


Figure 6c. Incremental annual cooling electricity cost per square foot of glazing for a 1,540 square foot residential home in Fresno, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

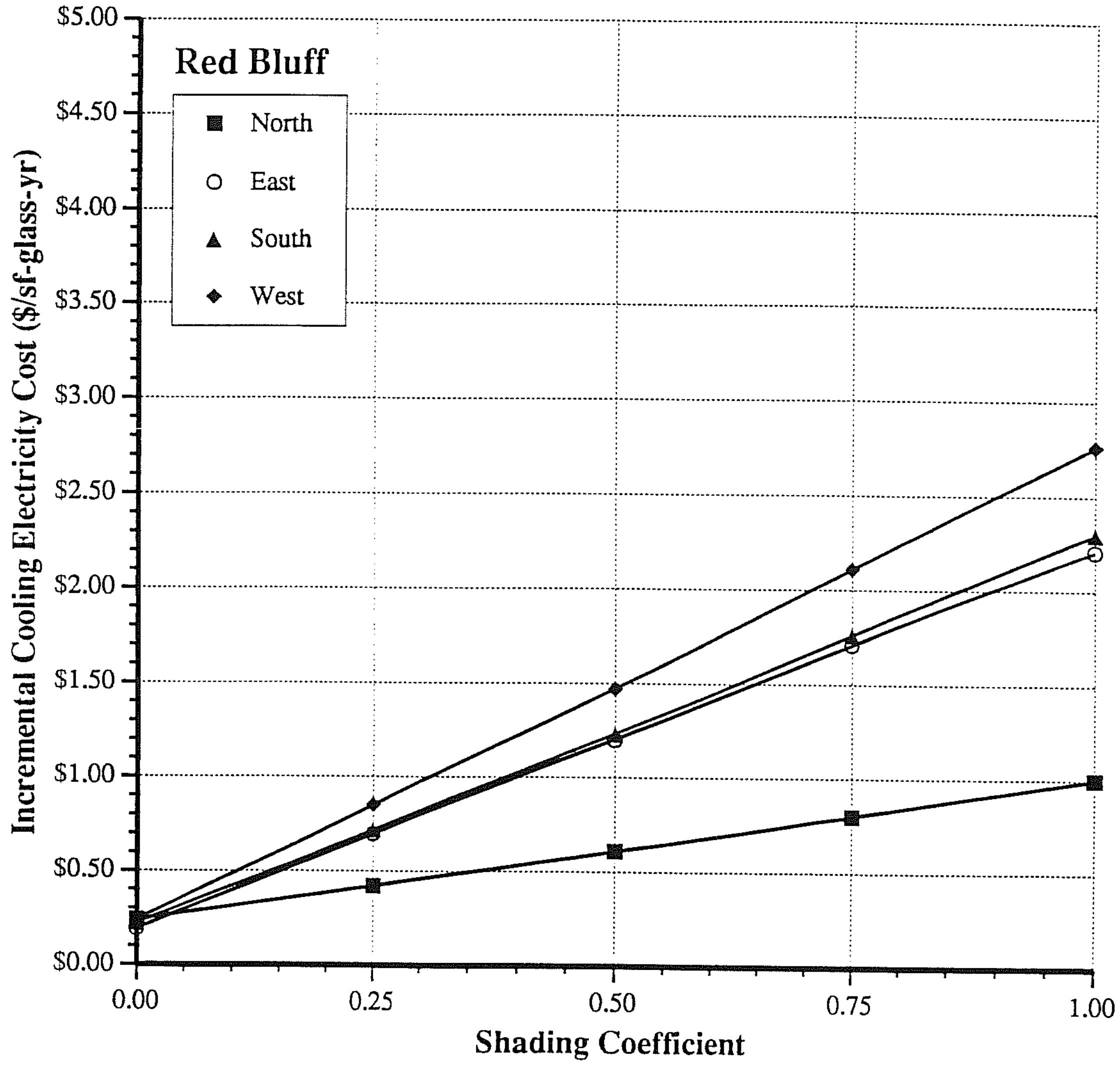


Figure 6d. Incremental annual cooling electricity cost per square foot of glazing for a 1,540 square foot residential home in Red Bluff, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

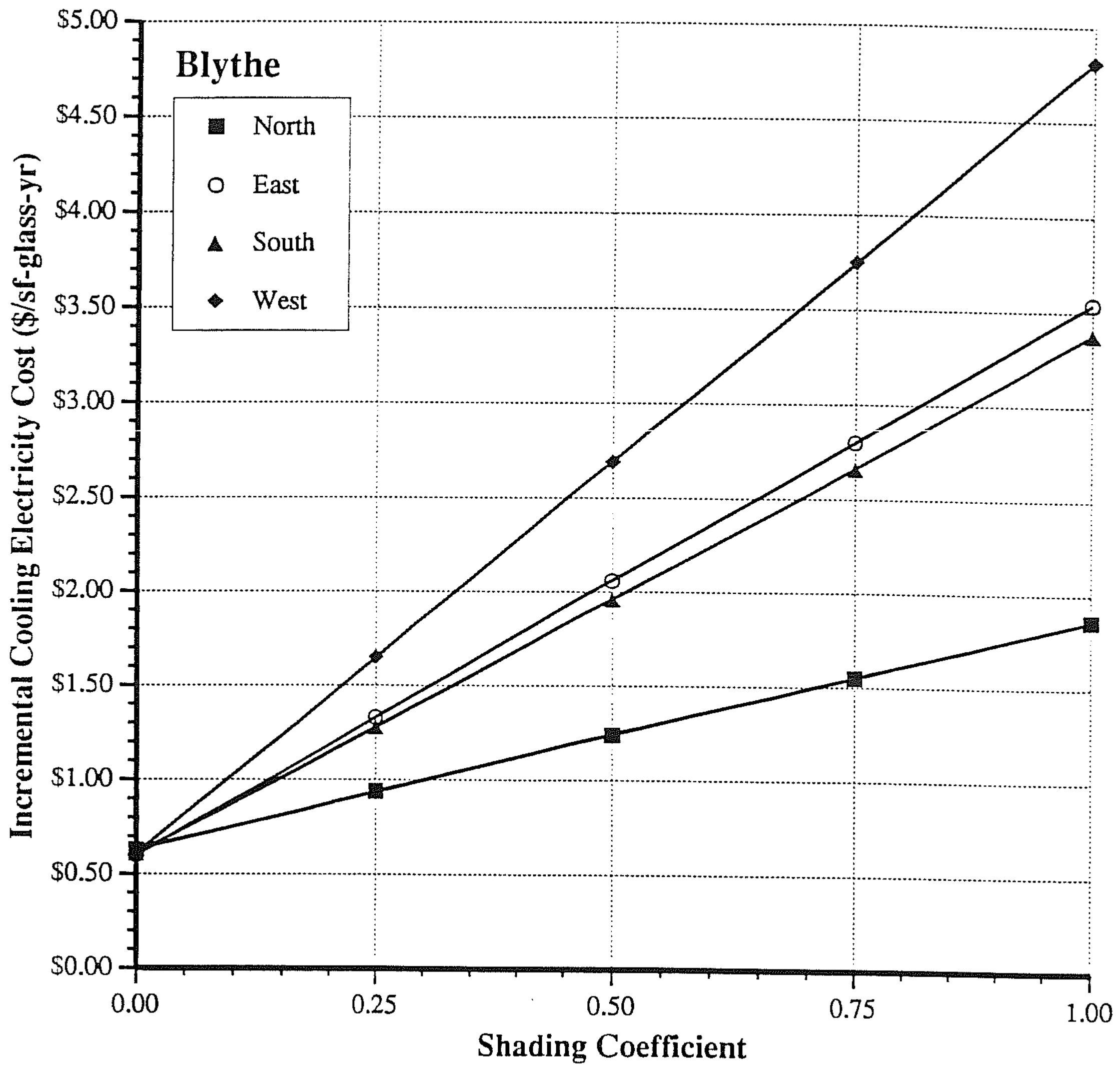


Figure 6e. Incremental annual cooling electricity cost per square foot of glazing for a 1,540 square foot residential home in Blythe, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

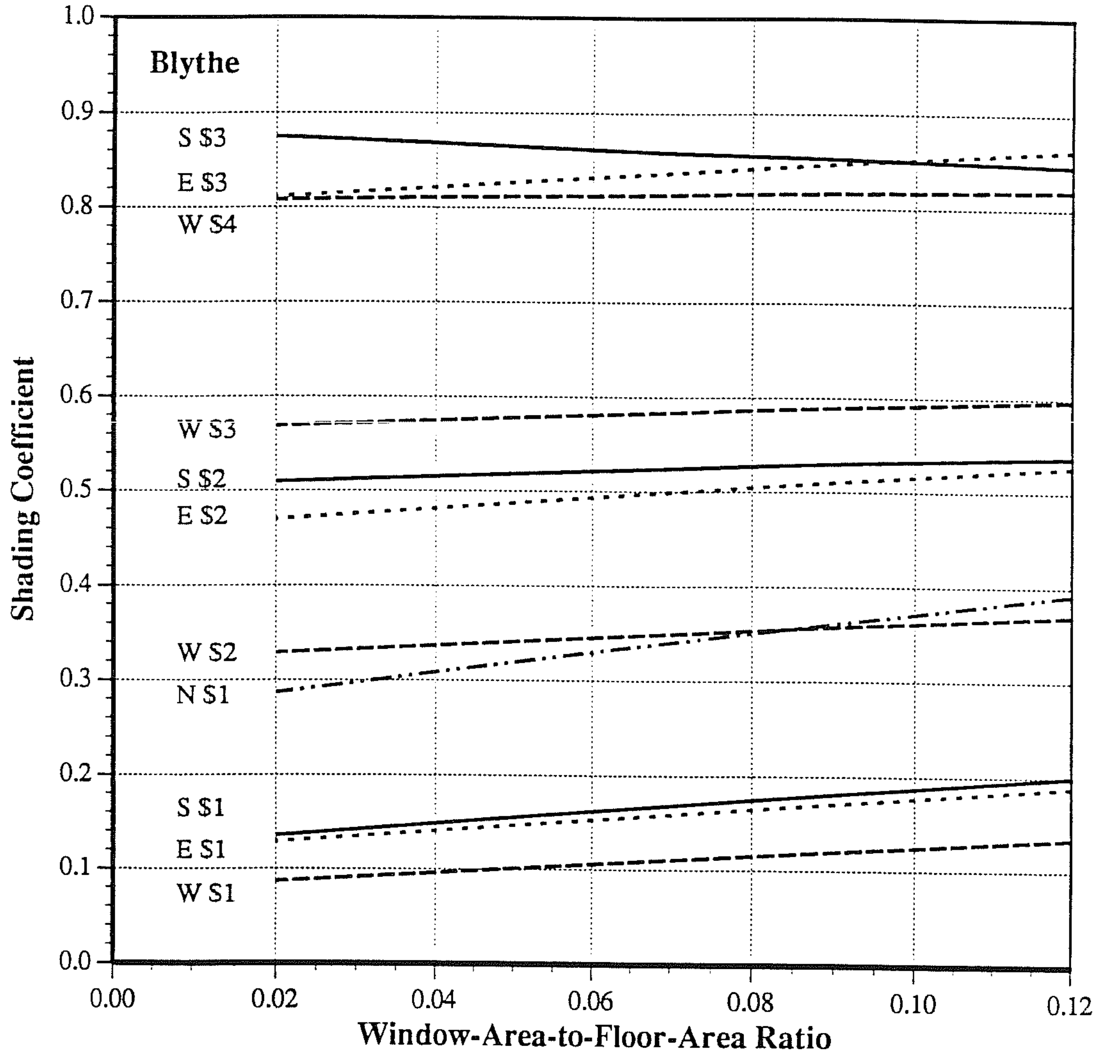


Figure 7. Incremental cooling energy cost per orientation for a 1,540 square foot residential home in Blythe, California given variations of shading coefficient and window-area-to-floor-area ratio for the base case configuration. Noted on the graph is the orientation, i.e. N=North, E=East, S=South, and W=West, and the incremental cooling energy cost in $/sf-glazing-year.

conductance associated with the outdoor air temperature. For example, in Blythe, the percentage of the incremental peak demand due to the solar gains versus glazing conductance is 40% / 60% or 7% / 11% of the total building peak demand for a north facing window (4% WFR). For a west facing window, the solar gain component of the peak demand is significantly larger: 75% / 25% of the incremental peak demand or 27% / 10% of the total building peak demand. Therefore, west facing windows produce the highest incremental peak demand, on the order of 15 to 33 W/ft^2-glazing, for all five climates; whereas, the south, east, and north orientations (in decreasing order) produce a relatively lesser incremental peak demand, on the order of 7 to 16 W/ft^2-glazing (Figures 8a-8e). For a building with 14% glazing equally distributed on all four orientations, a change in shading coefficient from 1.0 to 0.5 will produce a 50% reduction in incremental peak demand in all climates. For demand side management programs, this may aid in reducing the need for future peak capacity.

Although the major benefit in reducing peak demand will be realized by utility companies, the homeowner may capture additional savings if replacement of the existing air conditioning system is in order. Since this is unlikely, the mechanical system savings presented here will be de-emphasized. The peak demand is directly related to the sizing of the air conditioner or chiller. If peak demand is reduced, additional cost savings may be obtained by downsizing the equipment. The climates of Blythe, Red Bluff, and Fresno require nearly the same cooling capacity for a given total building peak demand, whereas Sacramento and Riverside require a larger cooling capacity for a given total building peak demand for values greater than 10 W/ft^2-glazing (Figure 9). For example, in Blythe, a change in shading coefficient from 1.0 to 0.5 for 14% WFR produces a reduction in the total peak demand from 33.21 to 27.55 W/ft^2-glazing. This translates into a decrease in cooling capacity of 0.67 tons of refrigeration or \$3.11/ft^2-glazing (at \$1000 per ton) for Blythe, and 1.04 tons or \$4.82 for the same decrease in total peak demand in Sacramento.

The total building cooling energy savings is given for alternate configurations of the base case prototype in Figure 10. These total cooling energy savings are due to a change in shading coefficient from 1.0 to 0.5. Parameters that cause a reduction of the admitted solar gain either inside or outside of the building produce the largest reduction in savings; i.e. two foot overhangs, the building situated in a built-up or metropolitan area, or interior shades. For example, a two foot overhang in Sacramento reduces the base case total cooling energy savings from \$0.80 to \$0.42/ft^2-glazing-yr. In Blythe for the same parameter, the savings is reduced from \$1.48 to \$0.88/ft^2-glazing-yr. Other parameters

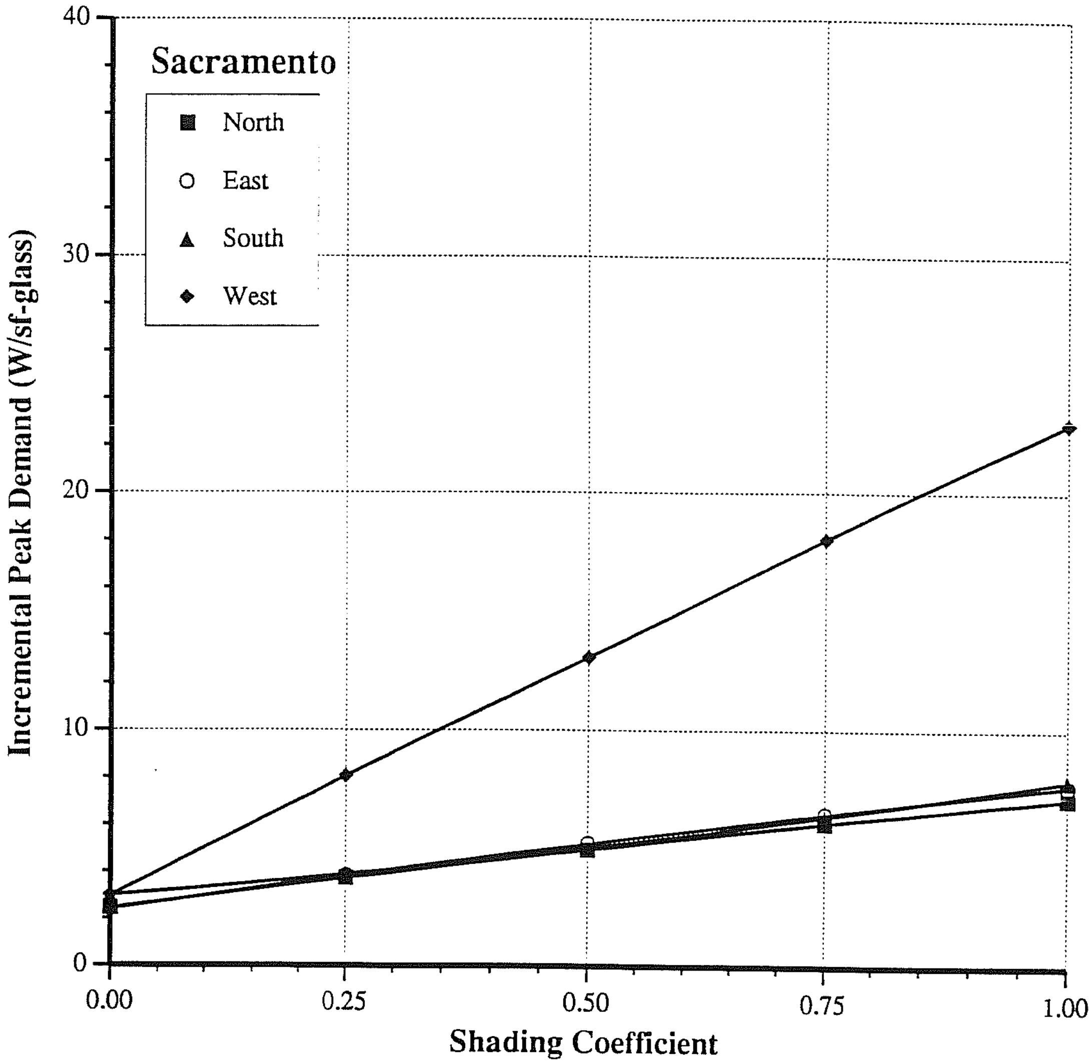


Figure 8a. Incremental cooling peak demand per square foot of glazing for a 1,540 square foot residential home in Sacramento, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

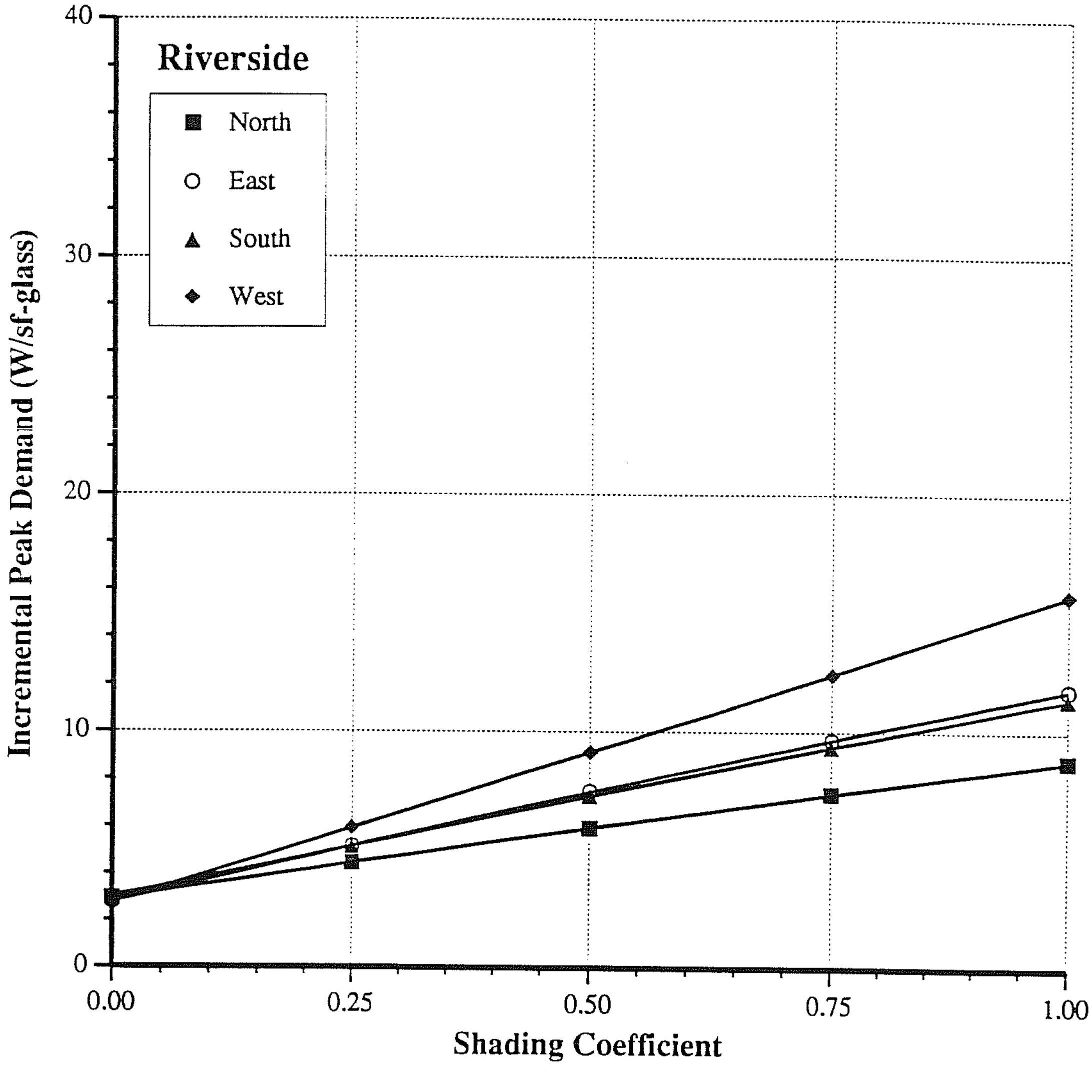


Figure 8b. Incremental cooling peak demand per square foot of glazing for a 1,540 square foot residential home in Riverside, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

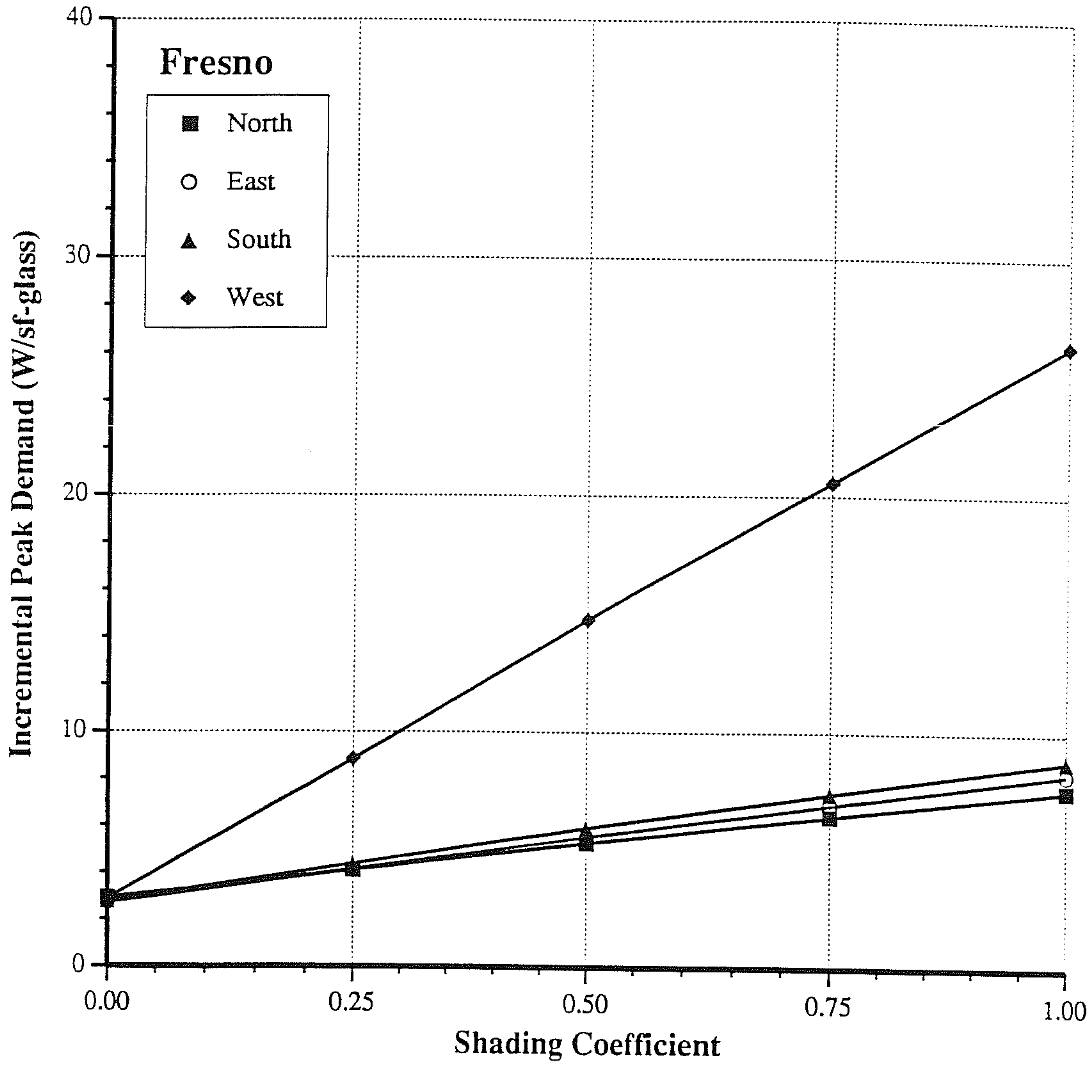


Figure 8c. Incremental cooling peak demand per square foot of glazing for a 1,540 square foot residential home in Fresno, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

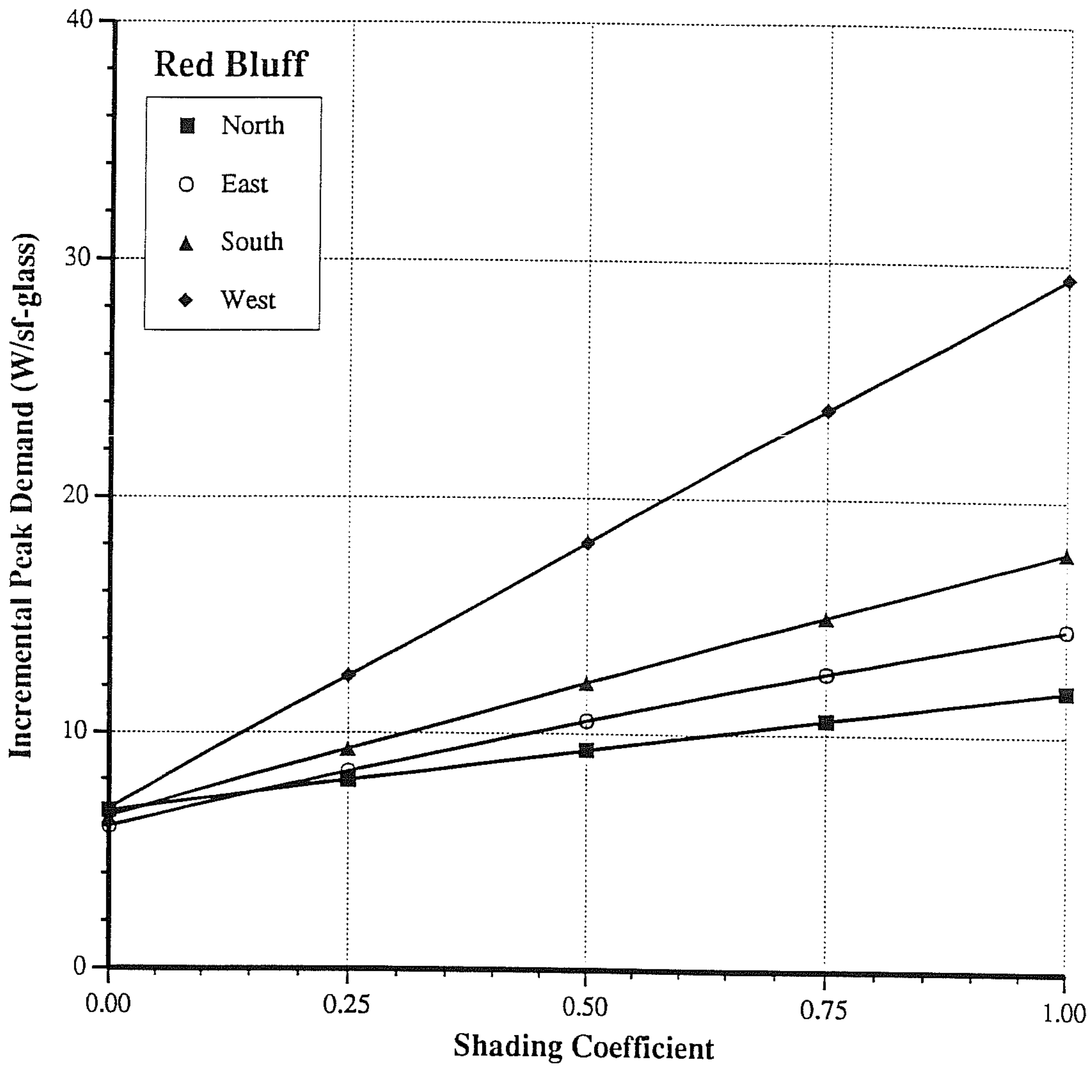


Figure 8d. Incremental cooling peak demand per square foot of glazing for a 1,540 square foot residential home in Red Bluff, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

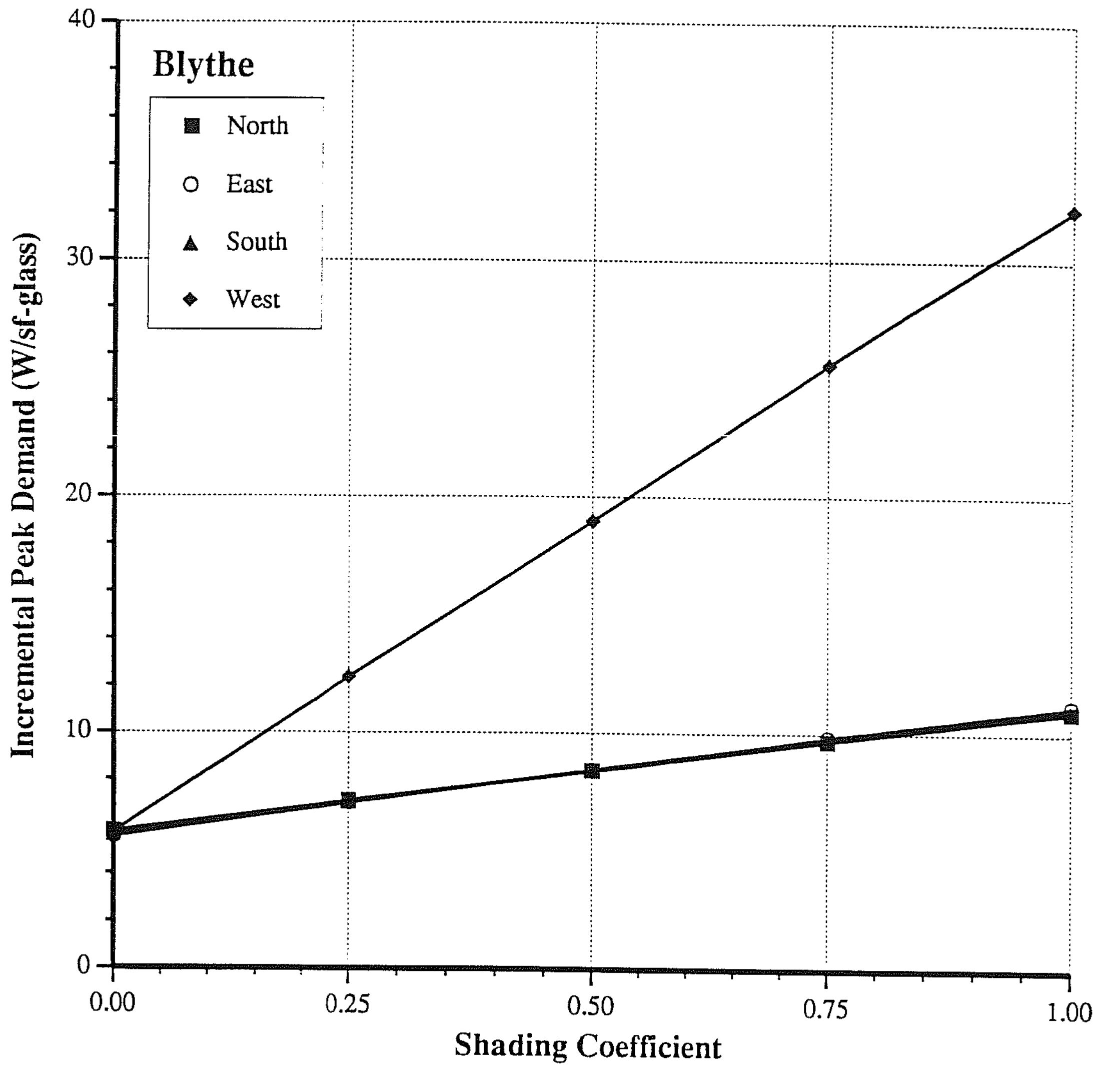


Figure 8e. Incremental cooling peak demand per square foot of glazing for a 1,540 square foot residential home in Blythe, California for a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

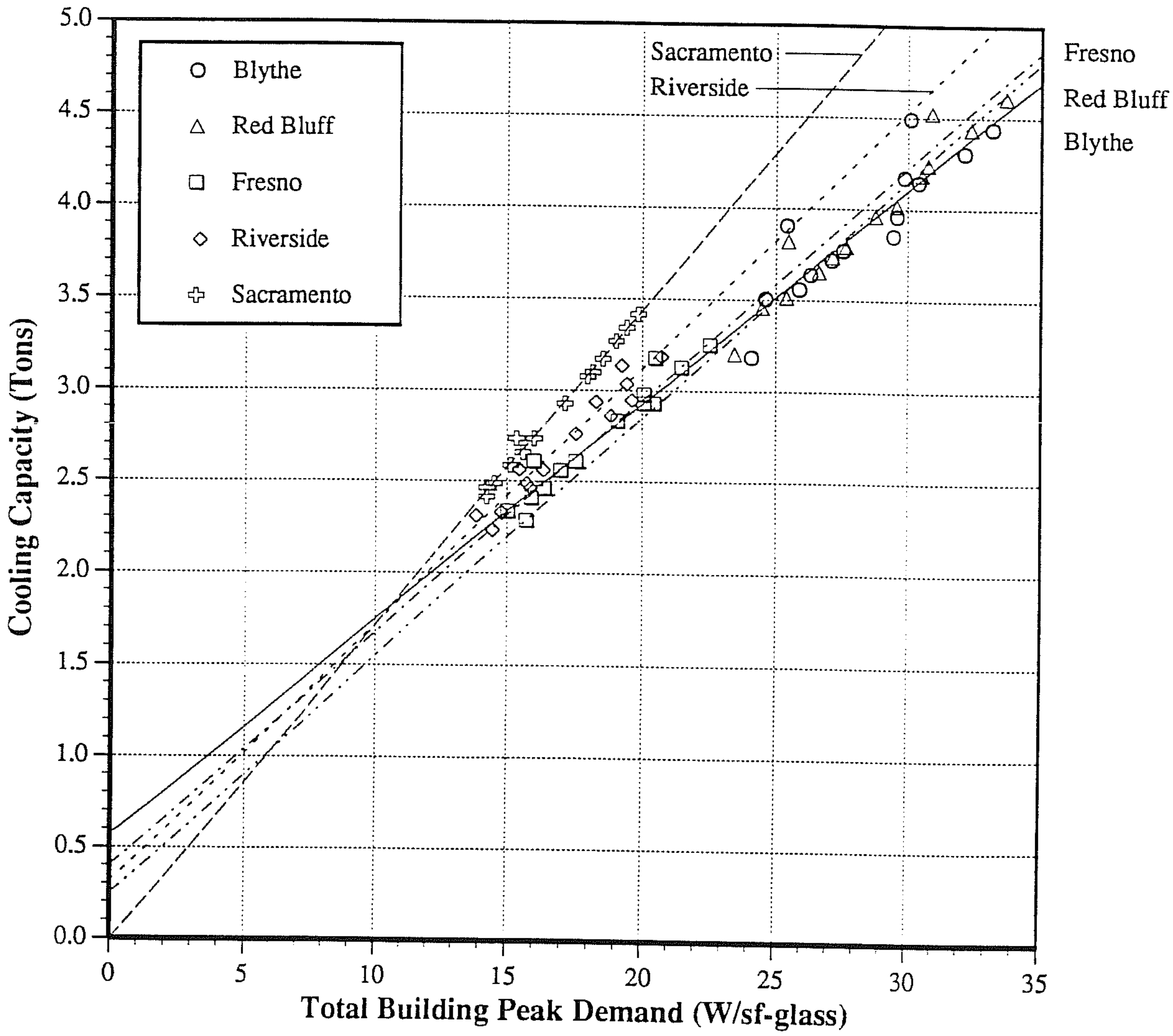


Figure 9. Total building peak demand due to cooling per square foot of glazing versus total cooling capacity for a 1,540 square foot residential home in five California climates for a glazing area of 3.5% window-area-to-floor-area ratio per orientation. Datapoints include the base case prototype and the alternates that represent a range of housing characteristics for shading coefficient values of 0.5 and 1.0.

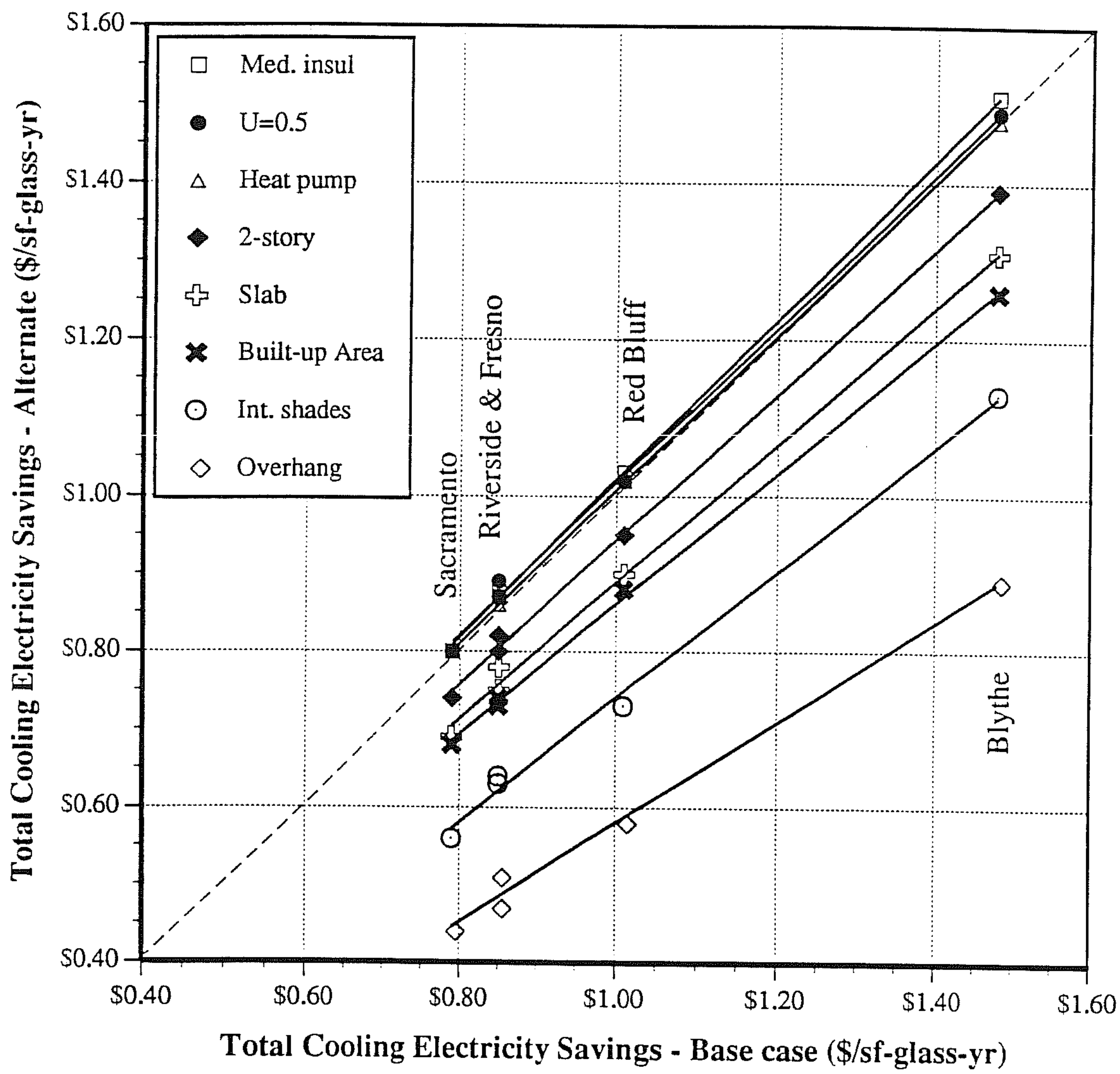


Figure 10. Total building cooling electricity savings per square foot of glazing due to a change in shading coefficient from 1.0 to 0.5 for alternate building configurations in five California cities. Glazing area has a 3.5% window-area-to-floor-area ratio per orientation.

such as increased insulation levels, double pane glazing, or a heat pump produce essentially no change in total cooling energy savings over the base case.

To facilitate comparisons between climates, we have graphed the total building peak demand for various cities on one plot even though the peak demand for the alternate prototype configurations occur at different times (Figure 11). The residential prototype is envelope dominated (as opposed to internally load dominated as with commercial office buildings), so the peak demand will be more closely tied to the external weather conditions. For the summer, this difference in peak times between climates will produce negligible differences in peak demand, on the order of 2 to 4%, since the ambient weather conditions are roughly the same over the peak summer months. As expected, the total peak demand of the alternative prototypes versus the base case prototype varies in a linear manner with changes in geographical location. The relative performance of each alternative for a given climate cannot be attributed directly to the glazing conductance or solar gain components of the total peak demand since each alternative configuration affects other components of the total peak load, such as the wall or roof conductance, or affects the glazing peak demand components in a non-comparable manner. The peak demand for the alternate prototypes is given for shading coefficient values of 1.0 and 0.5.

From the perspective of the material scientist, defining the cost-effective boundaries of required glazing characteristics may aid future product development. Equation 2 above provides a useful method for determining these values. Only the incremental heating and cooling energy costs have been used to define the total incremental energy cost savings. The incremental heating cost deficit has been included in the total incremental cost since for the moderate climates such as Sacramento and Red Bluff (HDD(65_F) = 2,764 & 2,904), this contribution can be significant. Incremental fan energy savings increase with shading coefficient but in relatively insignificant magnitudes. Mechanical system replacement can significantly improve total cost savings but we have assumed that this option will not be a typical occurrence. For example, in Blythe, the total building energy savings of \$1.38/ft^2-glazing caused by a reduction in the shading coefficient from 1.0 to 0.5 consists of +\$1.48 due to cooling, -\$0.15 heating, and +\$0.05 fan (14% WFR). In Sacramento, however, the total savings of \$0.53/ft^2-glazing consists of +\$0.79 due to cooling, -\$0.27 heating, and +\$0.02 fan energy savings.

These cost effective boundaries are illustrated in Figures 12a and 12b for the extreme and moderate climates of Blythe and Sacramento given varying desired energy savings and an existing or pre-retrofit shading coefficient value of 1.0. If one assumes a shading

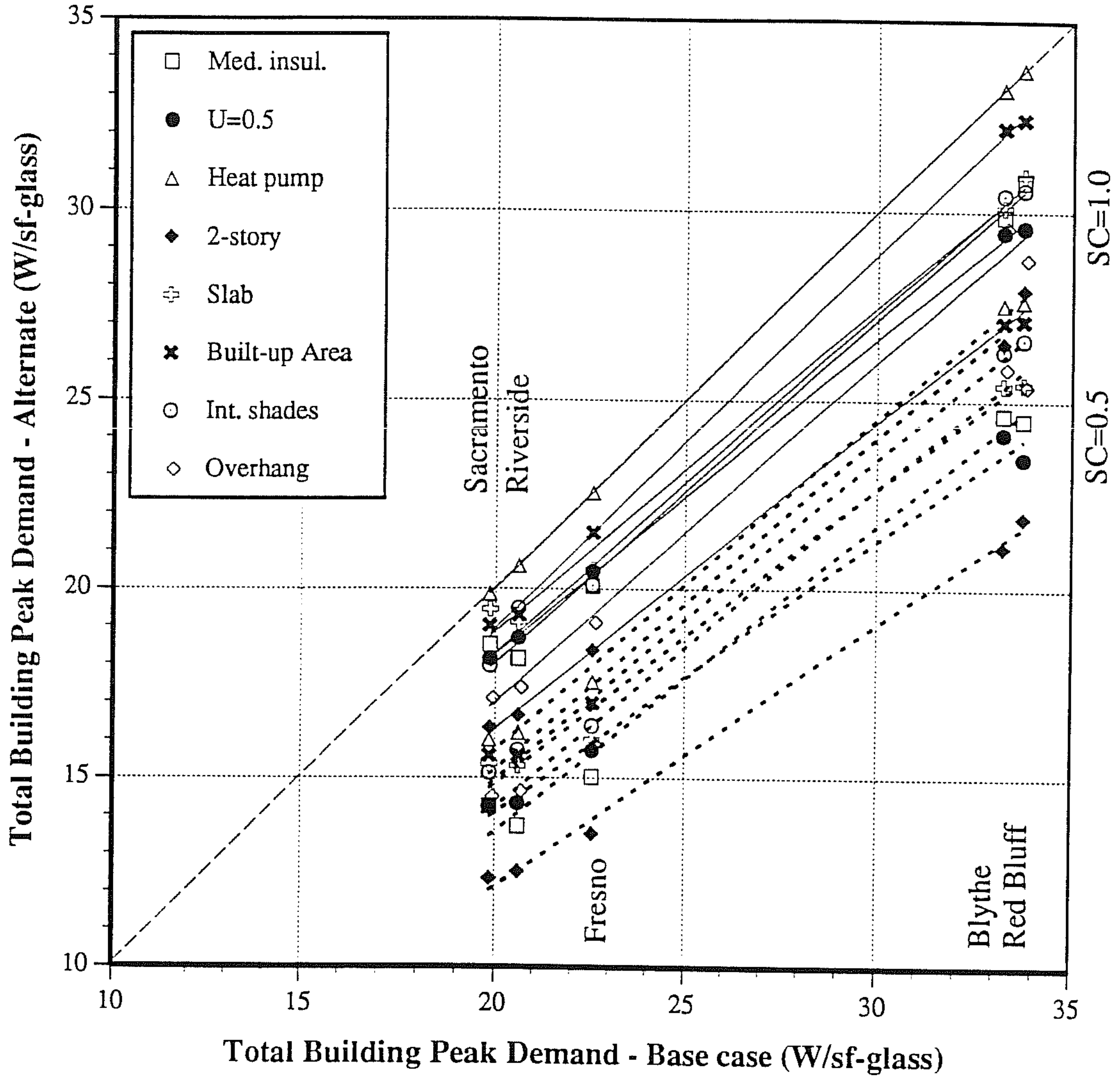


Figure 11. Peak demand per square foot of glazing area for shading coefficient values of 1.0 and 0.5 for alternate building configurations in five California cities. Glazing area has a 3.5% window-area-to-floor-area ratio per orientation.

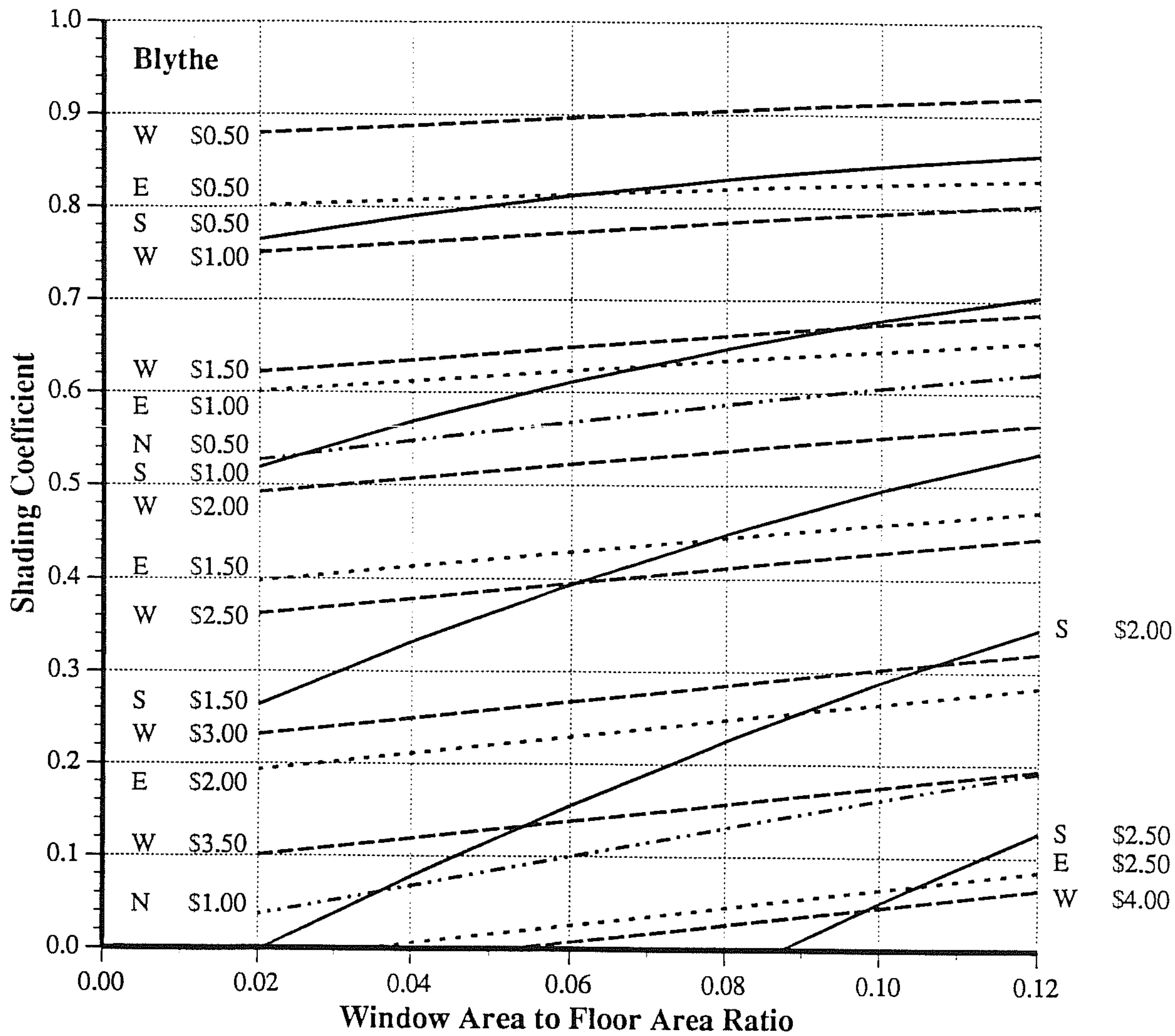


Figure 12a. Incremental heating and cooling cost savings per square foot of glazing due to a change in shading coefficient from 1.0 to the y-coordinate value of shading coefficient and the x-coordinate window-area-to-floor-area ratio for the base case configuration of a 1,540 square foot residential home in Blythe, California.

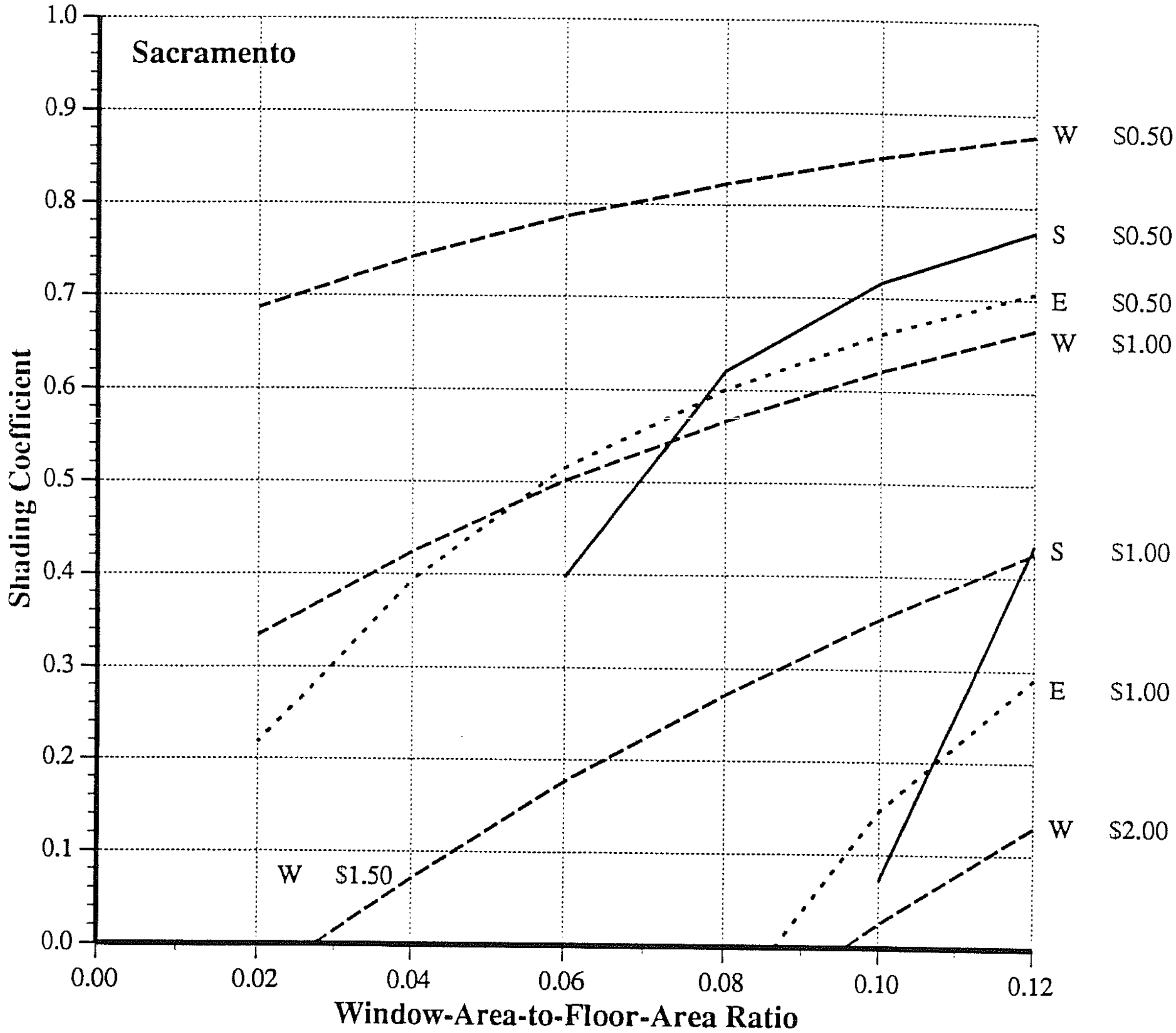


Figure 12b. Incremental heating and cooling cost savings per square foot of glazing due to a change in shading coefficient from 1.0 to the y-coordinate value of shading coefficient and the x-coordinate window-area-to-floor-area ratio for the base case configuration of a 1,540 square foot residential home in Sacramento, California. Note that a north-facing window yields no cost savings.

coefficient limit of 0.5 for existing or emerging durable spectrally selective coatings, retrofits in Blythe for west facing windows will result in a \$2.00 to \$2.25/ft^2-glazing incremental energy savings (depending on the area of the glazing), for the south \$1.00 to \$1.60, for the east \$1.25 to \$1.40, and for the north \$0.50 to \$0.60. For the same retrofit in Sacramento, however, a west facing window will yield \$0.75 to \$1.25/ft^2-glazing incremental energy savings, south \$0.00 to \$0.80, east \$0.00 to \$0.75, and north \$0.00. If the desired incremental energy savings is \$0.50/ft^2-glazing and the glazing area per orientation is 4%, the required shading coefficient values per climate vary from 0.39 east and 0.74 west for Sacramento; 0.47 E, 0.21 S, and 0.79 W for Fresno; and 0.55 N, 0.81 E, 0.79 S, 0.89 W for Blythe (missing orientations indicate that this incremental energy savings can not be achieved, see Table 5). If the building has any of the alternate characteristics such as an overhang or interior shading, the required shading coefficient for a desired incremental energy savings will be further reduced.

Several efforts are now ongoing that will speed the introduction of these *new* technologies into the residential market. The Pacific Gas and Electric Company is considering a residential program that will offer shading coefficient incentives for new construction; e.g. for shading coefficient values between 0.51 and 0.65, there is a \$1.00 incentive per square foot of glazing, for values between 0.41 to 0.50, \$2.00, and for values less than 0.41, \$4.00 (PG&E, 1992). These incentives are intended to overcome the market barriers and may be effective in spurring adoption of these new technologies.

Development of Spectrally Selective Prototypes

We discussed the potential for adapting the types of spectrally selective glazings that are now available for new windows to retrofit situations with representatives of most of the concerned glass and window manufacturers. On two occasions we had the opportunity to conduct intensive face-to-face discussions with industry groups. The Workshop on Spectrally Selective Glazings was sponsored by DOE, CIEE, SCE and other utilities and manufacturers. In addition to two days of open presentations we also had several smaller sessions to discuss specific subjects. The second forum for discussion of these issues is the National Fenestration Rating Council (NFRC). We formed a Task Group on Laminates under the Optical Properties Subcommittee to develop new methods and standardize procedures for measuring and calculating the properties of laminated window structures. Our first task was to categorize the options for retrofitting existing residential windows with spectrally selective glazings as follows:

Table 5. Required Shading Coefficient for a Given Glazing Area and Desired Heating and Cooling Energy Cost Savings

	WFR	Cooling and heating cost savings per square foot of glazing over SC=1.0 for base case prototype: $0.50	$1.00	$1.50	$2.00	$2.50	$3.00	$3.50	$4.00
		SCreq	SCreq	SCreq	SCreq	SCreq	SCreq	SCreq	SCreq
Sacramento									
East	2%	0.218							
	4%	0.394							
	6%	0.516							
	8%	0.601							
	10%	0.661	0.147						
	12%	0.707	0.291						
South	6%	0.397							
	8%	0.620							
	10%	0.717	0.072						
	12%	0.773	0.435						
West	2%	0.687	0.334						
	4%	0.742	0.424	0.070					
	6%	0.787	0.501	0.176					
	8%	0.823	0.567	0.271					
	10%	0.852	0.621	0.354	0.026				
	12%	0.876	0.667	0.426	0.130				
Riverside									
North	10%	0.393							
	12%	0.536							
East	2%	0.235							
	4%	0.471							
	6%	0.604							
	8%	0.686	**0.212**						
	10%	0.741	0.383						
	12%	0.779	0.492						
South	4%	0.475							
	6%	0.692							
	8%	0.779	0.464						
	10%	0.828	0.609	0.241					
	12%	0.859	0.689	0.461					
West	2%	0.632	0.156						
	4%	0.747	0.357						
	6%	0.825	0.508	0.097					
	8%	0.881	0.617	0.287					
	10%	0.921	0.698	0.427	0.044				
	12%	0.952	0.760	0.531	0.231				

Example:
Mr. Jones has an east-facing window that will cost $1.00 per square foot of glazing to install.
The area of the glazing is 8% of the floor area.
His home is in Riverside.
The required glazing shading coefficient is 0.212.

Table 5. Required Shading Coefficient for a Given Glazing Area and Desired Heating and Cooling Energy Cost Savings

	WFR	Cooling and heating cost savings per square foot of glazing over SC=1.0 for base case prototype: $0.50	$1.00	$1.50	$2.00	$2.50	$3.00	$3.50	$4.00
		SCreq	SCreq	SCreq	SCreq	SCreq	SCreq	SCreq	SCreq
Fresno									
North	10%	0.131							
	12%	0.246							
East	2%	0.377							
	4%	0.469							
	6%	0.542							
	8%	0.600	0.051						
	10%	0.647	0.166						
	12%	0.684	0.262						
South	4%	0.211							
	6%	0.529							
	8%	0.659							
	10%	0.732	0.308						
	12%	0.779	0.474						
West	2%	0.758	0.490	0.215					
	4%	0.792	0.541	0.278	0.001				
	6%	0.822	0.588	0.338	0.070				
	8%	0.849	0.630	0.394	0.136				
	10%	0.872	0.667	0.444	0.199				
	12%	0.892	0.700	0.491	0.259				
Red Bluff									
North	4%	0.003							
	6%	0.106							
	8%	0.200							
	10%	0.282							
	12%	0.352							
East	2%	0.653	0.298						
	4%	0.667	0.321						
	6%	0.681	0.344						
	8%	0.693	0.367	0.017					
	10%	0.705	0.388	0.044					
	12%	0.716	0.409	0.071					
South	2%	0.539							
	4%	0.637	0.181						
	6%	0.703	0.332						
	8%	0.751	0.443						
	10%	0.785	0.526	0.171					
	12%	0.812	0.588	0.297					
West	2%	0.776	0.532	0.283	0.030				
	4%	0.803	0.571	0.331	0.083				
	6%	0.827	0.608	0.378	0.136				
	8%	0.849	0.641	0.421	0.187				
	10%	0.869	0.672	0.462	0.236				
	12%	0.887	0.700	0.499	0.282	0.044			

Table 5. Required Shading Coefficient for a Given Glazing Area and Desired Heating and Cooling Energy Cost Savings

	WFR	Cooling and heating cost savings per square foot of glazing over SC=1.0 for base case prototype: $0.50	$1.00	$1.50	$2.00	$2.50	$3.00	$3.50	$4.00
		SCreq	SCreq	SCreq	SCreq	SCreq	SCreq	SCreq	SCreq
Blythe									
North	2%	0.527	0.036						
	4%	0.548	0.068						
	6%	0.568	0.100						
	8%	0.587	0.131						
	10%	0.605	0.162						
	12%	0.622	0.192						
East	2%	0.802	0.600	0.397	0.193				
	4%	0.808	0.612	0.413	0.211	0.006			
	6%	0.814	0.623	0.429	0.230	0.026			
	8%	0.820	0.634	0.444	0.248	0.046			
	10%	0.825	0.645	0.459	0.266	0.065			
	12%	0.831	0.655	0.473	0.283	0.085			
South	2%	0.764	0.519	0.263					
	4%	0.791	0.569	0.332	0.078				
	6%	0.813	0.611	0.394	0.154				
	8%	0.831	0.648	0.448	0.225				
	10%	0.846	0.678	0.495	0.290	0.051			
	12%	0.858	0.705	0.536	0.347	0.126			
West	2%	0.879	0.751	0.622	0.492	0.362	0.232	0.101	
	4%	0.888	0.762	0.635	0.507	0.379	0.250	0.119	
	6%	0.896	0.773	0.648	0.523	0.396	0.268	0.138	0.007
	8%	0.905	0.784	0.661	0.538	0.412	0.285	0.157	0.027
	10%	0.913	0.794	0.674	0.552	0.429	0.303	0.176	0.046
	12%	0.920	0.804	0.686	0.566	0.444	0.320	0.194	0.065

I. Replace the entire window frame with a sealed IG unit incorporating spectrally selective coatings.

II. Add a second pane with spacer to create unsealed IG.

III. Glue a spectrally selective laminate to the existing glass.

IV. Replace the existing glass with an advanced glazing of the same thickness

   a. monolithic absorbing glass

   b. coated glass

   c. laminated glass with interior coating

The first option is the most thorough and certain solution, as well as the most expensive. Proven coating technology with excellent optical characteristics can be used in a protected environment. Furthermore, the window will approximately triple in thermal resistance because of the air gap and because the type of coating possible in this configuration will have a low emissivity. Optional gas fill could increase the resistance even further. The disadvantage, of course, is the expense of replacing an otherwise good window.

Option II, also creates an IG unit with the potential for thermal resistance nearly equal to the manufactured unit in Option I. In this case, however, the coating is not fully protected. New materials may be required to provide selectivity equal to that of coatings that can be used in sealed IGs. Also, the appearance of this type of retrofit may not be considered acceptable by some buyers.

Option III results in a better protected environment overall than Option II, but some controversy still exists over the resistance of these coatings to damage at the unsealed edges of the laminate structure. This is by far the least expensive option at about \$1.25-\$2.00/ ft^2 including installation. In this configuration the active coating layer is usually protected by an abrasion resistant hardcoat on a polyester substrate. These high emissivity layers hide the low emissivity of the active layer underneath. Some products have a thin overcoat applied directly to the coating that is partially transparent to the thermal infrared allowing a reduced emissiviity. The emissivity of uncoated glass is about 0.84, while reduced-emissivity coatings fall in the range of about 0.75-0.25 which would lower the U-value from about 1.06 to the range of 1.01-0.69. This reduction in U-value is only about 5-35% because the exterior surfaces of windows have high rates of conductive and convective heat transfer which short circuit the radiatve resistance of the low-e surface. Even these modestly reduced emissivities have only been demonstrated for products with low visible transmission, but the same method could probably be applied to high Tv products.

The cost of materials alone for replacing the glass under Option IV is on the order of \$0.60 /ft^2 for tinted glass to as much as \$2.00 /ft^2 for coated glass. Including labor, however, would approximately double the cost compared to the glue-on film of Option III. On the other hand, replacing glass is easier for an amateur installer to do properly than gluing on a film, so a do-it-yourself project could be even less expensive. At the very minimum this approach should be taken whenever breakage occurs. Options IVb and IVc both require some additional materials research or at least some product testing, but they would give better optical performance than IVa.

Options III and IV are probably the only viable methods for retrofitting large numbers of existing windows simply because of the cost factor, and despite other performance benefits of Options I and II. One manufacturer has developed a series of glue-on films with excellent spectral selectivity. At present, the cost of these coatings is 1.5 to 2 times higher than conventional glue-on products. The durability of these films is also in question. The manufacturer claims, however, that the films can be applied so that edge degradation is minimal. Furthermore, silver-based films of lower transmission made by other manufacturers have been in use for many years. These films generally have a good track record with little or no edge degradation but there are reports of coating failure or delamination after about five years. Failure is usually reported in wet or humid climates whereas in hot dry climates of the type for which spectrally selective coatings are most useful, Ag coatings have been known to last for the lifetime of the window. A demonstration project to test both the performance and the durability of these coatings is called for.

Almost, the same considerations on durability hold for laminated replacement glazing (Option IVc) as well as the Option III glue-ons discussed above. In this case the central area of the film is surely well protected, but the edges might still be susceptible to moisture. A good sealing system might be easier to apply to a replacement laminate than to the glue-on laminate. The replacement laminate, however, would be thicker than the original glass because two pieces of glass would be joined. An alternative would be to use thinner panes of glass in the laminate such as single strength rather than double strength or even thinner special glass. Options IVa and IVb are relatively low cost and require no modifications to the window structure. IVb would give better performance and color than IVa, but durability is a serious problem for IVa, requiring further materials research.

Research Plan for Durable Coatings

The glue-on laminate (III) and replacement laminate (IVc) of the previous section may have adequate durability and this should be verified by a demonstration project with one or more utilities and manufacturers. Southwall, Courtaulds, and 3M have all expressed interest in participating in this project. If the products fail this test, then some product engineering will be required to make a better seal and possibly it may come to material research on the coating itself. The coated replacement glass (IVb), however, definitely needs further materials research now.

As mentioned above, Ag-based coatings have the best optical performance of any spectrally selective product, but they may not be sufficiently durable.. One alternative is to use a coating without any metal layers such as a classic all-dielectric multilayer. This type of coating in principle can achieve any desired level of optical performance. The large number of thick layer required, however, is considered prohibitively expensive to manufacture at this time. Advances in production speed and maximum number of layers in window coating equipment are rapidly increasing, so that an all-dielectric coating may be possible in the next few years.

At the opposite extreme, a coating could use a metal other than silver that would have comparable optical properties and improved durability. Several of the transition-metal and rare-earth oxides,, as well as some other nitrides and borides, have the required properties. The reason that these apparently promising materials have not been exploited is because of the difficulty in fabricating them as thin films with the proper crystalline microstructure. We have been experimenting with new types of ion-beam techniques that can be used to induce the necessary structure (Rubin, 1991). Unfortunately, existing commercial sputter coaters do not yet have the same capability as our research systems. We have been working with the equipment suppliers and glass coaters to accelerate the introduction of this technology. Not only the deposition process but also the new ion sources are being developed at LBL

Conclusions

Based on the high proportion of existing residences built with clear single glass and the results of our performance modeling, we conclude that there is a large potential to save energy in California through the use of retrofitted spectrally selective glazings.

For the moderate California climates that have a higher population, such as Sacramento, Fresno, and Riverside, one can expect a total incremental energy savings of $0.53 per square foot of glazing if all the existing windows (SC=1.0) are retrofit with a spectrally selective coating or film (SC=0.5, WFR=14%, base case prototype). For the hotter California climates that have a lower population, such as Red Bluff and Blythe, one can expect a larger total incremental energy savings of $0.80 to $1.38/ft^2-glazing. Incentive programs being considered by the public utilities would help to make selective retrofits cost effective.

Some existing options can be used immediately. Other potential solutions exist which require additional testing in the laboratory or in demonstration projects. The introduction of spectrally selective glazings can begin with demonstration projects using existing technologies in hot climates or with utility sponsored rebate or incentive programs that target west glazing and/or unobstructed glazing only to meet the criteria of cost effectiveness.

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